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TV WHITE SPACE NETWORK PLANNING AND CO-CHANNEL INTERFERENCE ESTIMATION

Master of Science Thesis

Examiners: Professor Mikko Valkama, Professor Markku Renfors
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ABSTRACT

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The frequencies that are suitable for radio communication are a scarce resource and some of the licensed frequency bands are considered to be underexploited. The future visions comprehend using the spectrum more efficiently, but avoiding the interferences by the means of cognitive radios. A cognitive radio is a device that can observe the radio conditions of its surrounding environment, learn from this and use this information for adjusting its operation to the current state of the environment. One of the licensed frequency bands that have been opened for cognitive radio testing is the terrestrial TV band. The regionally or temporally free channels in the TV band are called the white space. This thesis discusses the white space network planning and the co-channel interference estimation. The co-channel interference is due to the Digital Terrestrial Television (DTT) network. Especially this thesis has an emphasis on the rural wireless broadband application. The main focus is on a pilot case providing a fixed wireless broadband to a few locations in Kirkkonummi using the Espoo TV and radio mast.

The starting point for the network planning is determining a free channel so that no interference is caused to the primary user of the frequency band, that is, the DTT network. After selecting the free channel, the downlink coverage and capacity is estimated with the network planning tool Atoll. Some of the white space studies made so far have indicated that the uplink connection limits the coverage of the network due to the co-channel interference in the base station antenna from the DTT transmitters. In order to investigate this issue, a Matlab estimation function to estimate the co-channel interference power will be introduced in this thesis. The estimation function is based on the ITU-R P.1546 propagation model. The estimation function will be evaluated with the interference power measurements from three different locations, from Jokela, Pasila and Espoo. The co-channel interference will be used to estimate the uplink coverage in the Espoo pilot and also to calculate the amount of usable channels based on the interference level. The network planning, added with the uplink coverage estimation, will be evaluated with field tests.

The most important conclusion in this thesis is that estimating the uplink limitation is an essential part of the white space network planning even with point-to-point connections. The estimation has its own challenges, but rather good results can be achieved with the existing propagation models with small changes. Furthermore it was found that using such devices in the white space band that are not designed for such purposes is challenging. In addition to the required cognitive capabilities, the white space devices demand a wide operation region to be able to use the best channels in the area. Also a good selectivity and strict emission mask are required to overcome the different interference scenarios in the white space band.

TIIVISTELMÄ

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Signaalinkäsittelyn ja tietoliikennetekniikan koulutusohjelma
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Radiotoimintaan soveltuvat taajuudet ovat rajallinen resurssi ja kaikki lisensseillä suojatuilla taajuusalueilla toimivat järjestelmät eivät hyödynnä koko taajuusaluetta tehokkaasti. Tulevaisuuden visioihin kuuluu näiden taajuusalueiden tehokkaampi käyttö, häiriöitä aiheuttamatta, käyttäen ns. kognitiiviradioita. Kognitiiviradio on laite joka pystyy havainnoimaan ympäristöään ja muokkaamaan toimintaansa näiden havaintojen perusteella vallitsevaan tilanteeseen sopivaksi. Yksi lisensoiduista taajuusaluista, joka on avattu kognitiiviradion testaamista varten, on maanpäällinen televisioverkko. Tässä työssä käsitellään kognitiiviradioiden verkkosuunnittelua TV-kanavien taajuusalueella, taajuuksia uudelleen käyttäen TV-peittoalueiden ulkopuolella. Työssä tutkitaan myös TV-verkosta aiheutuvan saman kanavan häiriön estimointia. Työssä keskitytään erityisesti maaseudun langattomaan laajakaistaverkkoon. Avainasemassa on pilottihanke, jossa tavoitteena oli kiinteän langattoman laajakaistayhteyden tarjoaminen muutamaan kohteeseen Kirkkonummen alueella käyttäen Espoon TV- ja radiomastoa.

Suunnittelun lähtökohtana on ensinäkin käytettävän kanavan valinta niin, ettei TV-vastaanottimille aiheudu häiriötä. Vapaan kanavan määrittämisen jälkeen tehdään verkkosuunnitelma verkkosuunnittelutyökalu Atollilla alalinkin peittoalueen ja kapasiteetin määrittämiseen. Aiemmat tutkimukset vapaiden TV-kanavien sekundäärisestä käytöstä ovat indikoineet ylälinkin rajoittavan verkon peittoaluetta, johtuen TV-verkon aiheuttamasta saman kanavan häiriöstä tukiaseman antennille. Häiriötason määrittämiseksi tässä työssä tehdään Matlab-estimointifunktio saman kanavan häiriön tehotasolle. Estimointifunktio päätettiin toteuttaa ITU-R P.1546 etenemismallilla. Estimointifunktion toimintaa arvioidaan kolmesta eri paikasta, Jokelasta, Pasilasta ja Espoosta tehdyillä spektrimittauksilla. Saman kanavan häiriötehotasoa käytetään sekä ylälinkin peittoalueen ja kapasiteetin määrittämiseen Espoon pilotti tapauksessa, että häiriötason perusteella käytettävien kanavien määrän arvioimisessa. Ylälinkin arvioidulla toiminnalla täydennettyä verkkosuunnitelmaa verrataan lopuksi kentällä tehtyihin mittauksiin verkon toiminnasta.

Tärkeimpiä johtopäätöksiä työssä on, että vaikka kyseessä olisi kiinteä yhteys kahden pisteen välillä, niin ylälinkin suuntainen yhteys voi rajoittaa solun kokoa huomattavasti ja ylälinkin toiminnan estimointi on hyvin olennaista. Estimoinnissa on omat haasteensa, mutta lupaavia tuloksia saatiin olemassa olevalla etenemismallilla pienin lisäyksin. Vapaiden TV-kanavien hyödyntäminen tällä hetkellä saatavilla laitteilla on haastavaa. Vaadittujen kognitiivisten ominaisuuksien lisäksi laitteilla täytyy olla laaja toiminta-alue parhaiden kanavien hyödyntämiseksi, sekä hyvä selektiivisyys vastaanotossa ja tiukka emissiomaski lähettimessä erilaisten häiriöskenaarioiden välttämiseksi.

PREFACE

The research behind this thesis was conducted in a six month period during the years 2011 and 2012 at the Digita Oy. The research was partly funded by the Finish Funding Agency for Technology and Innovation (Tekes). The thesis was aimed to provide technological background for exploring the commercial possibilities of the TV white space.

First I would like to thank my instructor Kari Heiska from the Digita. Our weekly so called therapy sessions were important part in structuring this thesis to the way it is now. I also like to thank Kari for promoting the use of thesis workers in the projects and that way making it possible also for me to do my thesis in a very interesting project in the cutting edge of the wireless communication and acquire valuable experience for my future career. Special thanks goes to my supervisors professors Mikko Valkama and Markku Renfors for all the effort in making this thesis academically acceptable both in content and language wise.

From my colleagues from Digita I would like to thank among others Annemarie Hjelt for helping me with the antenna design, Airi Mölsä for the guidance with the planning tool Atoll and Nicolas Le-Bail, Juhani Lindqvist and Sampo Heikkinen for helping in the field measurements. Last but not least I would like to thank my parents Jarmo and Heli and my sister Suvi for all the support during the years and also my dear friends from the University for making the studying so much more fun.

On April 18, 2012, in Tampere

Sauli Niskanen

Contents

ABBREVIATIONS

ACI	Adjacent Channel Interferences
ACLR	Adjacent Channel Leakage Ratio
ACS	Adjacent Channel Selectivity
BPSK	Binary Phase Shift Keying
C/I	Carrier to Interference ratio
CPE	Customer-Premises Equipment
CRS	Cognitive Radio System
dBµV/m	Desibel microvolts per metre
dBm	Power in decibels referenced to one milliwatt
dBW	Power in decibels referenced to one watt
DTT	Digital Terrestrial Television
DVB-T	Digital Video Broadcast Terrestrial
ECC	Electronic Communications Committee
EIRP	Effective Isotropic Radiated Power
FCC	Federal Communications Commission
I/C	Interference to Carrier ratio
I/N	Interference to Noise Ratio
ITU	International Telecommunications Union
M2M	Machine-to-Machine
MAN	Wireless Metropolitan-Area Network
MAPL	Maximum Allowed Pathloss
MIMO	Multiple Input Multiple Output

QAM	Quadrature Amplitude Modulatio
QPSK	Quadrature Phase Shift Keying
RSSI	Receiver Signal Strength Indicator
SNR	Signal to Noise Ratio
S-SIG	The Weightless Standards-SIG
TDD	Time Division Duplex
TVWS	Television White Space
UHF	Ultra High Frequency
WAN	Wide-Area Network
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WSD	White Space Device
OFDM	Orthogonal Frequency-Division Multiplexing
FDD	Frequency-division duplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
MAC	Medium Access Control

SYMBOLS

A	Aperture area of an antenna
B	Bandwidth in Hertz
d_1	Distance from the transmitters in meters
d_2	Distances from the transmitters in meters
D_f	Frequency dependent term
D_h	Asymptotic term defined by horizon distances
$E(f, d, h_a, h_{eff}, t)$	Electric field strength calculated with ITU-R P.1546 model.
$E_{fs}(f, d)$	Electric field strength calculated with free space loss
f	Frequency in MHz
G_r	Antenna gain of the receiver
G_t	The transmitter antenna gain
h_a	Antenna height above ground
h_b	Height of the base station in meters in Okumura-Hata model
h_{eff}	Effective antenna height to the direction of the receiver averaged over distances of three kilometers and 15 km from the transmitter
h_m	Height of the mobile in meters in Okumura-Hata model
k	Boltzmann's constant 1.38*10-23 Ws/k
n	Number of the Fresnel zone
p	Power density of an antenna
P_t	Transmitted power
r	Distance between antennas
t	Time percent in ITU-R P.1546 model

T_e	Temperature of the environment in Kelvin’s
λ	Wavelength of the signal in meters

1 INTRODUCTION

The consumers' demand for mobile bandwidth is rapidly growing. This growth does not show any signs of slowing down. The amount of smartphones, tablets and other intelligent mobile devices is only increasing and so does the demand for high-bandwidth applications and services [1]. The frequency band allocated to data transmission today does not seem sufficient to cover the bandwidth demands of the future. This has led to studying the licensed spectrum areas that are temporarily or regionally unused. An unlicensed user could exploit the unused spectrum of the licensed service as long as it does not cause interference to the licensed system.

One area of the radio spectrum that has received a lot of interest lately is the so called TV white space. In Europe and somewhat similarly in almost all other parts of the world, the 470-790 MHz band is licensed for terrestrial broadcast television [2]. The high transmission powers and poor tolerance for co-channel interference makes the channel reuse factor very high for the broadcasting system. In addition, when the TV transmissions were analog, the analog TV needed wide frequency guard bands. After the transition to the digital TV, the analog TV channels were of course released, but also the guard bands are wider than needed for the more spectrum efficient digital TV. As a consequence from all of this, there is lot of unused spectrum locally depending on the density of the TV transmitters on the area. This unused spectrum could be exploited by the means of new wireless technologies without causing harmful interference to the licensed users of the band. These wireless technologies rely on the cognitive radios. The cognitive radio terminology refers to a radio device which has the ability to sense the external environment, learn from the history and make intelligent decisions to adjust its transmission parameters according to the current state of the environment [3].

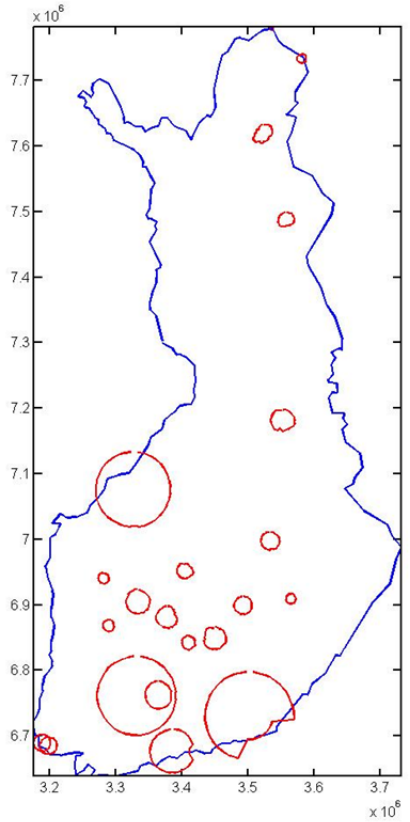

Figure 1.1 *Contours of the channel 27*

The Figure 1.1 illustrates locally unused areas on the channel 27 in Finland. The contours refer to the areas where receiving of the transmission in certain channel is estimated to fulfill the thresholds for the adequate reception. In Finland the channels are in practice free depending on the location, but not on the time since the transmitters are always on.

In 2009 an act was passed in Finland to enable testing of the cognitive radios in the TV white space. According to the press release from the Ministry of transport and communications, the Cognitive Radio Systems (CRS) will be allowed to use the frequency range of 470-790 MHz, in such a way that the CRS do not interfere with the other radio communications. [4]

1.1 Scope of the Thesis

Digita is taking part in the Finnish Funding Agency for Technology and Innovation (TEKES) Trial program. Digita’s project focuses on the business opportunities in the use of the TV white space frequency band. Related to this project, there was a pilot case on providing a wireless broadband access to three locations in Kirkkonummi. It was decided to use the Digita’s Espoo television and radio transmission mast for the base station antenna. The used devices are fixed Worldwide Interoperability for Microwave Access (WiMAX) devices converted to the white space band.

The topic of this thesis is the planning of the network and documenting the different aspects related to it. In the planning process it was decided to take the co-channel interference from the Digital Terrestrial Television (DTT) transmitters to the white space network also into consideration. This part included spectrum measurements from three antennas in different locations. One was the antenna installed for the network planned in this thesis and two others were installed earlier for the white space tests. Based on these measurements, a Matlab function was made to estimate the interference signal strength of the co-channel DTT transmitters to the white space base station. Based on these interference levels, some conclusions were made on the actual coverage and capacity of the network, due to limitations in the uplink connection.

1.2 Related Studies

The planned white space broadband network is first of its kind in Finland. Same kinds of pilots are being done at least in United States, United Kingdom and South Africa. In United States a device manufacturer Carlson Wireless has set up a pilot in northern California to provide rural broadband to Yorok reservation [5]. The reservation stretches 44 miles along the Klamath-Trinity River in Del Norte and Humboldt countries. Due to its challenging landscapes, the Internet access has been very limited in the Reservation. Microwave links cannot solve the problem, because the microwave frequency demands line of sight links and this has been practically impossible due to the landscape and limitations in building masts in the area. White space is hoped to solve the problem since Ultra High Frequency (UHF) band signals penetrate obstacles far better than the microwave signals and so possibly the Reservation can be covered building only three new masts [5].

In the United Kingdom a TV White Space Consortium, consisting of the largest technology and media companies in the country, has established a white space rural broadband trial in Cambridge. Although Cambridge itself has a good broadband access, some neighboring villages suffer from a poor broadband service. It is hoped that the good propagation characteristics of the white space frequencies could be demonstrated in the trial [6]. In Western Cape, South Africa there is a pilot project going on with a goal to connect all the schools in the area. The network is planned to have capacity between five to 10 Mbps with coverage up to 10 km. [7]

1.3 Structure of the Thesis

Chapter two explains the white space concept and its current regulatory status. This includes the methods for determining the available channels and regulations from Federal Communications Commission (FCC) and Electric Communications Committee (ECC). There is also general information about interference and noise and different interference scenarios in the white space operation and protection ratios. In the third chapter the fixed wireless broadband network planning is covered along with general information on the propagation models.

In the fourth chapter the standards and technologies related to white space operation at the moment are briefly introduced. The fifth chapter is about the network planning of the Kirkkonummi pilot case. In the sixth chapter the Matlab estimation model is explained and in the seventh chapter the measurements and results are presented. Chapter eight includes the summary and conclusions.

2 WHITE SPACE CONCEPT

The frequency band 470-790 MHz has been reserved for licensed operation for Digital Terrestrial Television. TV white space refers to the unused pieces of the spectrum in this band. The white space operation means that an unlicensed user could exploit this unused spectrum with devices that have the cognitive capabilities to ensure that interference is not caused to the licensed user.

This chapter introduces the possibilities known today for the White Space Device (WSD) to determine the unused spectrum of the DTT network. These are sensing, geo-location database and beaconing. After that, protection ratios are explained and the main points from the European ECC and American FCC regulations are introduced. Some basics about noise and interference are also explained as well as different interference scenarios in the white space operation in general.

2.1 Devices

CRS: A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state. It is able to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge, in order to achieve predefined objectives; and to learn from the results obtained. [8]

The white space devices (WSDs) are devices that can use the white space spectrum without causing harmful interference to the protected services. Non-interference to the protected services is achieved by employing the required cognitive capabilities. [9]

2.2 Exploring Usable Frequencies

There has been lot of research going on in Academic and industrial world in resolving how the white space devices could find the usable frequency bands. With the technologies available today there are three different approaches: sensing, geo-location database and beaconing. [2]

Sensing is used in many systems to avoid the intersystem interference and the technology itself is simple and well-known. However, in the white space operation there are certain problems using only sensing which are mentioned in the next subsection. Geo-location database is the main solution at the moment but the demands and specific system descriptions are still under development. Whether the beaconing method ever comes to usage or not, it is clearly a future solution and only in case the white space devices become common.

2.2.1 Sensing

Sensing is quite known method and it has also many consumer applications for example for detecting free channels for Wireless Local Area Network (WLAN). Sensing means that the transceiver listens to the intended channel, before operating on it, to determine whether the channel is used or not. Sensing is not however a totally reliable method [9]. The receiver antennas for broadcast TV are usually located on the roof tops of the buildings. A mobile WSD device in the ground level is very likely to receive much more attenuated signal than the TV receiver. This is due to shadowing of the surrounding buildings and the environment altogether. This can cause the mobile to determine that the signal level on the channel is so low that the receivers do not use it and the channel can be occupied. However the roof top antenna might have usable signal quality and the WSD using the same channel causes unwanted interference [9]. The situation explained above is depicted in Figure 2.1.

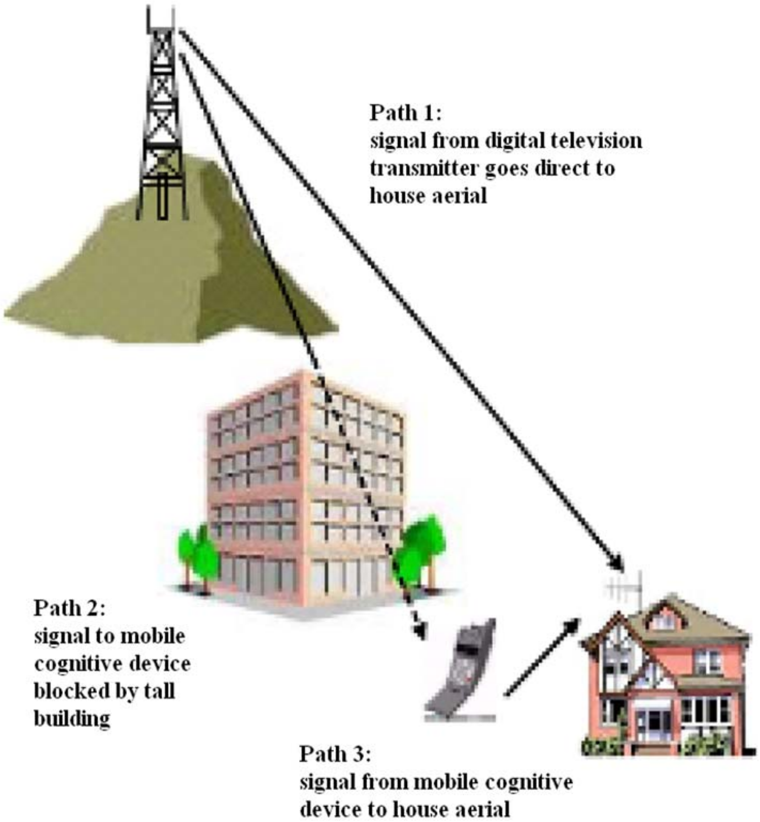

Figure 2.1. *Hidden node problem [9]*

This problem is not limited only to the mobile WSD's located lower than the TV receiver. Even an equal height fixed WSD antenna can have a different DTT signal strength than the DTT receiver nearby, depending on the properties of the environment. So the unoccupied channels are difficult to detect based solely on the DTT field strength measured by the white space device. Sensing is, however, very likely to be in the cognitive radios as an aid to support the decision. The geo-location database described in the next subsection cannot be aware of the whole frequency usage. For example in 2011 the radio microphones were decided to move from the 800 MHz band to the TV UHF band.

Most of the usage areas of these microphones will not be registered to the database, so sensing is needed in order to avoid interferences to the microphones. In practice the DTT signal levels can also differ from that of anticipated so sensing can provide valuable practical knowledge of the channel properties.

Solving the challenges in the sensing method has acquired academic interest, for example [10]. Although the commercial solutions at the moment are focused on the database method, the possibility to make the devices rely only on sensing is interesting. The usage scenarios for the WSD's would probably grow without the demand for reliable Internet connection to the database, for example, in the sensor networks applications.

2.2.2 Geo-Location Database

The most likely solution to this free channel detection problem is using a geo-location database [9]. The geo-location database concept is based on the idea that before the white space device can start operating, it has to contact some known and trusted database. The exact parameters are yet not standardized. It is proposed for example by Ofcom [11] that it is mandatory for a WSD to provide the database only its location. Also location accuracy, device type (fixed, portable or mobile) and preferences as to the amount of information that it receives, can be provided.

The database contains needed information for operating on the each geographical pixel or location. The database returns at least the usable frequency bands and allowed transmit powers on those frequencies [11]. It is not decided should the database calculate the transmitting power or should it only provide the information of the pixel and the WSD calculates itself the maximum allowed transmit power.

2.2.3 Beaconing

The beaconing method is the least studied at the moment and it probably will not be in the WSD devices at least in the beginning. The beaconing technology is quite similar to the database method. The difference is that there is a control signal giving all the needed information to operate on the area. The control signal could be sent from an external source for example the broadcast TV stations, the radio base stations or the licensed wireless communication providers.

The WSD would not be allowed to operate before receiving this control beacon and of course applying to the setup given in the message. The benefit compared to geo-location database is that the WSD does not need to know its location and establish connection to the database which can be time consuming in some cases. The downside is that the building of the beaconing network takes time and money and hence it is not taken into considerations, at least at this point of the white space research. The beaconing signal contours are also hard to define accurately due to location and time variation of the electric field strength. [9]

2.3 Noise and Interference

In this chapter, the basics of noise and interference are covered before introducing protection ratios. Thermal noise is caused by the random movements of the charge carriers in temperature over absolute zero. The noise power can be calculated as introduced in [12] with the Equation:

$$\mathrm{P_{n0}}(T_e, B)[\mathrm{dBW}] = 10 * \log(k * T_e * B) \tag{2.1}$$

in which k is the Boltzmann's constant $1.38*10^{-23}$ Ws/k, T_e is the temperature of the environment in Kelvin's, usually around 290 K and B is the bandwidth in Hertz. Besides thermal noise there is also receiver noise due to the components in the receiver that is amplifiers and mixers. This is described as the noise figure which is defined as the Signal to Noise Ratio (SNR) at the receiver input divided by the SNR at the receiver output. Because the amplifiers have gain, noise added in the later states does not have so much impact as the noise added in the first state.

In addition to noise, also interference degrades the operation of the network. Interference means disturbing signals from the same radio network or the other systems and devices. The basic definition to interference is that it is a disturbing signal from manmade device whereas noise is purely a physical phenomenon.

Interference can be categorized to two different types. First are the spurious emissions. Electrical devices, also other than the radio transmitters, cause spurious emissions in a large bandwidth. Most of the countries have regulations for the emissions that the devices have to fulfill before allowed to use in the country. Nevertheless, the spurious emissions cannot be completely avoided. The strength of the emissions is depended on the frequency so that it decreases when the frequency increases. Also number of the electrical devices in the environment impacts the strength of the emissions. The other type of interference is other intentional emission sources. This means the other radio transmitters that are intentionally using the same frequency band and raise the interference level on the band [12]. In the white space case the DTT transmitters can cause interference to the white space network. The white space transmitters are not allowed to interfere the DTT network because it is the licensed user of the band and its customers are paying for the interference free operation.

The actual disturbance level that the data signal has to overcome is noise plus interference. The interference always raises the combined noise and interference level, but if the interference is small enough related to the noise level, the addition does not have any effect on the operation of the system. This relation is described as Interference to Noise (I/N) ratio and is usually expressed in decibels. For example if noise level is -103 dBm and I/N is 0 dB hence the interference is also -103 dBm then the combined noise and interference level is -100 dBm, thus there is a three decibels increase. [13]

In the white space case these considerations are in the most of importance. First of all because the TV receiver has to be protected as the incumbent user and the rise in the television system interference level has to be minimized. Secondly, the DTT system causes interference to white space networks which has to be also considered in order to make fully functioning networks.

2.4 Protection Ratios

The communication systems need a certain SNR or Carrier to Interference ratio (C/I) for a reliable communication. SNR is the power ratio of the data signal power to average white Gaussian noise power that is mainly thermal noise, affected by the receiver noise factor. C/I is the power ratio between data signal carrier power and the interference power. In DTT system the sufficient signal level for reception is usually expressed in terms of C/I, so it is mostly used in this thesis. The quality of the received signal is also expressed with the Signal-to-Interference-plus-Noise ratio (SINR) which is data signal power ratio to aggregate interference power from all the transmitters in the same band plus the noise power [10].

Guizani mentions in [14], the predetermined protection ratio as the threshold SNR above which the quality of service is satisfactory in noise limited systems. According to ECC Report 148 [19], usually protection ratio is specified as a function of the frequency offset between the wanted and interfering signals over a wide frequency range. In this thesis the protection ratio is considered as in European Broadcasting Union document [18], where protection ratio is the limit for the WSD power in order to provide sufficient C/I ratio for the protected service. The protected service's C/I ratio is affected by the adjacent channel interference, the mitigation in receiver sensitivity and the co-channel interference. For this reason two different cases are distinguished for the protection ratio. One is the adjacent channel protection ratio and the other is the co-channel protection ratio. The adjacent channel protection ratio is the maximum allowed ratio between the interfering signal power and the protected service signal power in decibels. This is illustrated in the Figure 2.2.

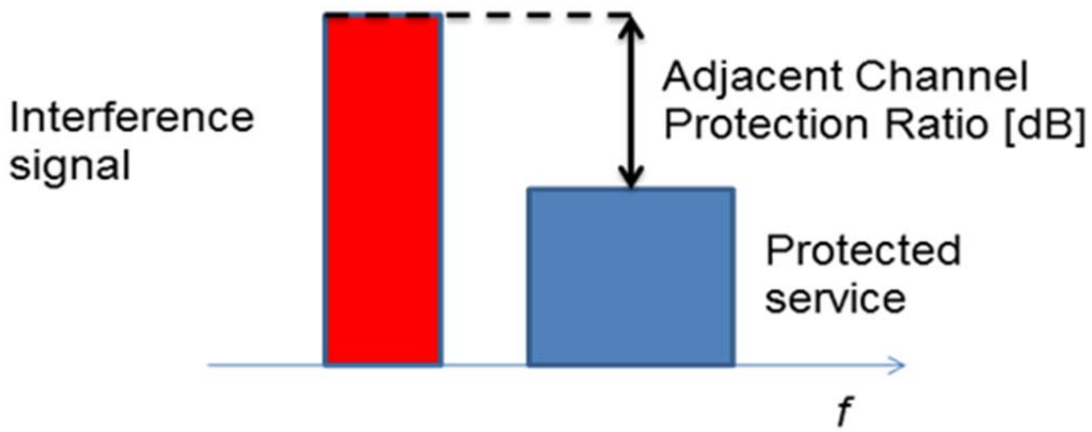

Figure 2.2 *The adjacent channel protection ratio*

The reason why the power of the WSD signal in the adjacent channel has to be limited in relation to the protected service is that it can cause adjacent channel interference or blocking to the receiver.

The adjacent channel interference power is dependent on the Adjacent Channel Leakage Ratio (ACLR) of the transmitter, Adjacent Channel Selectivity (ACS) of the receiver, the frequency offset between the signals and the interference signal power. The ACS is the ratio how much the receiver is able to attenuate the signal outside the intended channel. The ACLR is then the ratio how much of the transmitted power is leaked to the adjacent channels. The Digital Video Broadcast Terrestrial (DVB-T) receivers have the minimum requirements for the ACS and these minimum requirements should be used for the interference calculations. An example of the minimum selectivity requirements of the DVB-T receiver for interfering DVB-T/T2 signal is presented in the Table 2.1. From the receiver side the Table 2.1 shows the minimum requirements the receiver has to fulfill according to the specifications. For the interfering system it is the maximum limit how much the I/C can be in order to avoid interfering the reception.

Table 2.1. *The minimum required I/C for quasi error free reception with interfering DVB-T/T2 signal on the adjacent, other and image channels [16]*

Band	Signal Bandwidth MHz	Channel frequency raster MHz	Minimum I/C (dB)		
			Adjacent channels	Other Channels	Image channel
UHF IV	8	8	28	38	28
UHF V	8	8	28	38	28

Since the ASC is fixed the amount of adjacent channel interference can be affected with the ACLR of the WSD, the frequency offset and the transmission power of the WSD. If there are not fixed regulations for the ACLR it affects the protection ratio as described in the Figure 2.3.

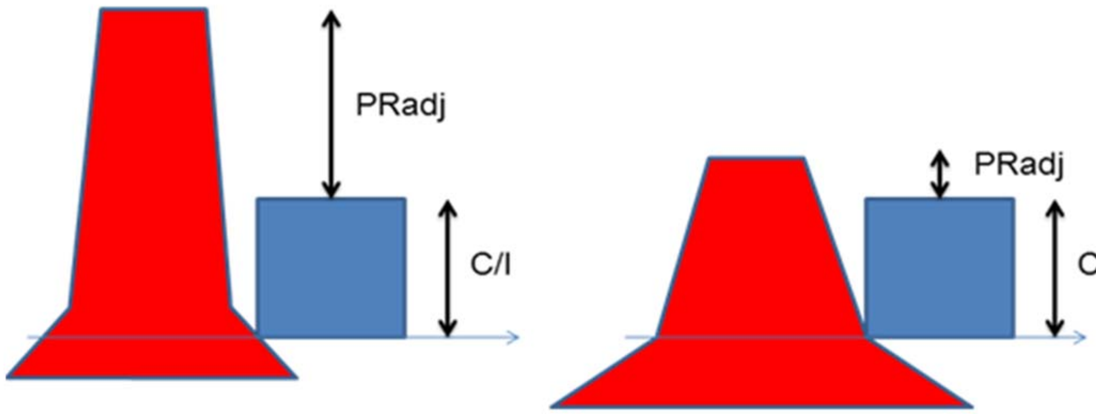

Figure 2.3 *The effect of the ACLR of the WSD to the adjacent channel protection ratio (PRadj)*

Figure 2.3 shows that with the same frequency offset the WSD power and hence the adjacent channel protection ratio has to be reduced if the ACLR is larger in order to sustain the sufficient C/I for the protected service. The FCC proposal is that the WSD's have fixed regulations for the ACLR. In this case the adjacent channel protection ratio is dependent solely on the frequency offset.

Like mentioned before, the adjacent channel protection ratio may not be only limited by the adjacent channel interference power. In some cases the adjacent channel interference power does not lower the protected service C/I ratio below the reception limit, but the protected service's reception quality is nevertheless affected. In white space literature this is usually referred to as blocking. As defined in ECC Report 148 [19], blocking means that high signal levels on the adjacent channels lowers the receiver ability to detect a low level wanted signal. A same kind of definition is presented in [15], where it is stated that the receiver blocking is an effect caused by a strong out-of-band signal, present at the input of the receiver. It reduces the receiver's ability to detect an in-band wanted signal. The blocking signal reduces the specified receiver sensitivity by a certain number of dB's. If the blocking is more severe problem than the adjacent channel interference, then it is the limiting factor for the adjacent channel protection ratio.

In the document [18], the co-channel protection ratio is defined to be equal to the Carrier to Noise ratio (C/N) of the protected service. This is depicted in the Figure 2.4.

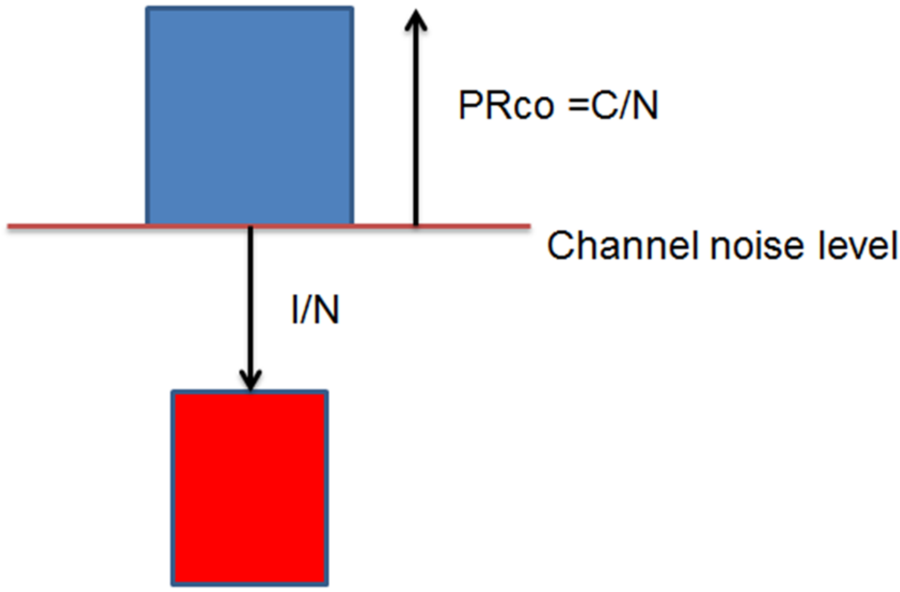

Figure 2.4 *The co-channel protection ratio (PRco).*

The C/N ratio is used since it is assumed that without the WSD transmission there is only noise in the channel. The C/N depends on the service and for example for the fixed DTT reception it is 21 dB and for the portable outdoor reception it is 19 dB. When evaluating the allowed WSD co-channel interference to the DTT network the actual co-channel protection ratio is not meaningful. In the white space case the co-channel is used outside the contour and hence it is assumed that the receivers in the contour edge have the minimum C/N for reception. Only the I/N ratio, which determines how much below the noise level WSD signal power has to be in order to preserve co-channel protection ratio, is important. The EBU scenario of the I/N ratio in the network planning is introduced in the Subsection 2.5.2. The co-channel protection ratio is not depended on the transmitter or the receiver capabilities and it can be preserved only by careful network planning of the white space networks.

2.5 Regulations

The radio spectrum has a vast amount of users and different kind of services. For example, the UHF I and II band has up until now been reserved for TV use. Those who wish to operate in the band have to apply for a license and pay for it, if granted. After this the band is reserved for the rightful owner and the authorities are obligated to make sure that the licensed owner’s service is not interfered. For the licensed and for unlicensed operation there are certain regulations that the system has to fulfill. These regulations are meant to make it possible to foretell what kind of interferences certain systems cause and so be able to mitigate interferences between the systems.

In this chapter there are the United States Federal Communications Commission’s (FCC) and the European Electric Communications Committee’s (ECC) proposals for the regulations for the white space cognitive radios. The focus is on the regulations concerning the fixed broadband devices. The FCC is more ahead and there is already devices and standards meeting the FCC regulations. The ECC proposal is more complicated and more under development and thus there are neither devices nor standards meeting the ECC regulations.

2.5.1 FCC Proposal

First of all, the commission has proposed to prohibit co-channel or first adjacent channel usage with the TV service channels inside the TV service contour for the fixed/access devices. The personal/portable devices could use the first adjacent channel, since it is assumed that the low transmitting powers of the devices does not cause interference to the TV services. [17]

Maximum limits for the WSD devices are 4 Watts of EIRP for the fixed and 100 mW for the personal/portable. If the personal/portable WSD uses the first adjacent channel the maximum EIRP is limited to 40 mW. The emission mask is defined so that the attenuation has to rise 55 dB from the highest average in-band power measured over 500 kHz bandwidth. The antenna height of the fixed WSD is limited to 30 meters above ground level. The guard distance for fixed WSD depends on the antenna height and whether it is a co-channel or an adjacent channel contour. The white space base station guard distances to the co-channel and the adjacent channel contours with different antenna heights according to the FCC proposal is listed in the Table 2.2.

Table 2.2 *The FCC Safety distances of the WSD base station [17]*

Antenna Height of Unlicensed Device	Required Separation (kilometers) From Digital or Analog TV (Full Service or Low Power) Protected Contour	
	Co-channel	Adjacent Channel
Less than 3 meters	6.0 km	0.1 km
3 – Less than 10 meters	8.0 km	0.1 km
10 – 30 meters	14.4 km	0.74 km

This kind of approach is very straightforward and makes the implementation easier. On the other hand it can be restrictive to some applications. The 30 m antenna height limit has raised already lot of discussion since for the rural broadband cases much higher base station antennas would be desired.

2.5.2 ECC Proposal

The ECC has proposed in its Report 159 the technical and operational requirements for the possible operation of cognitive radio systems in the white spaces of the frequency band 470-790 MHz. Whereas the FCC's method was quite traditional with a fixed guard band and power, the ECC has taken different approach with much more complicated system of calculating the allowed parameters based on the estimated interference.

The approach in the ECC regulation is the coverage probability of the TV contour. The TV transmission coverage is determined by a location probability. Location probability means that certain percent of the area can receive minimum field strength. Coverage is good when the location probability in an area is more than 95 %, that is more than 95 % of the locations within the area can receive the minimum field strength. Minimum field strength depends on the service and for the fixed DTT reception it is 55 dBµV/m. This is specified for a directional antenna facing the transmitter for optimal reception and with an antenna height of 10 m. The white space operation causes more interference to the TV system and hence a small degradation in the location probability is accepted. A proposed degradation by the ECC is 0.1 % that means a location probability of 94.9 % in the coverage edge. [9]

In practice it is discovered that 94.9 % probability leads to 20 dB I/N [18]. If the thermal noise level is assumed as -103 dBm the -20 dB I/N means limiting the white space signal strength so that it will not be over -123 dBm. The transmission power of the WSD is determined so that both the leakage power to the adjacent channels and the propagated power to co-channel is calculated with this limit and more restricting is chosen. For the co-channel case the guard distances become easily quite large. For example the 4 Watts of EIRP proposed by the FFC that is 36 dBm, requires path loss of 36 + 123 = 159 dB. With 30 m antenna that could mean a guard distance even as long as 40 km, depending on the propagation model. The limitation for the use of the adjacent channels comes also quite strict, so that the first usable channel could be third adjacent channel to DTT transmission.

2.6 Different Interference Cases in the White Space Operation

Four different types of interfering cases can be distinguished, the co-channel interference, the adjacent channel interference, blocking and receiver front end overloading. The co-channel, the Adjacent Channel Interference (ACI) and blocking are explained in the Subsection 2.4. Receiver Front end overloading is referred in [19], as a situation where strong signal in the adjacent channel makes the receiver to lose its ability to discriminate against the interfering signals at frequencies different than the wanted signal frequency. Above the overloading threshold the receiver does not necessarily fail immediately, but behaves in a non-linear way. In [37] it is said that when the receiver is overloaded, amplifier compression will reduce the receiver gain and hence the ability to detect weak signals. Or the non-linearities in the receiver that are excited by the overload, will allow unwanted signals to intermodulate. This may result a distortion product falling onto the wanted signal and effectively masking it. According to these sources the difference between the terms blocking and the front end overloading is not entirely clear. In the documents concerning the white space interference cases from the network planning point of view the causes for blocking and front end overloading are not defined in great detail. There is however good reason to use these different terms and this is also applied in this thesis. The use of term blocking distinguished from the ACI is explained in the Subsection 2.4. The receiver front end overloading is differentiated from the blocking so that blocking is more severe for the weaker wanted level signals and depends more on the ratio between the interference power and the wanted signal power. The receiver front end overload results are harder to estimate and the intermodulation products can affect also the reception of a good level wanted signal.

The white space base station can cause the co-channel interference to the DTT receiver's if the guard distance to the nearest same channel contour is too short in relation to the transmission power and the antenna height. The adjacent channel interference does not seem very likely inside the contour. If assumed that the fixed white space base station cannot use the first adjacent channel inside the contour, then the emission mask of the transmitter and the propagation loss should attenuate the signal to a sufficiently low level. This assumption should be valid in the case of fixed/access device since the FCC regulations prohibit the use of adjacent channel and the ECC regulations leads to so low transmission power that the adjacent channel usage is practically impossible for the fixed/access device. Outside the contour, the first adjacent channel interference is possible near the TV contour edge which leads to a safety distance in the use of first adjacent channel also. The signal is attenuated by the transmitters emission mask in the first adjacent channel, which makes the guard distance very short in relation to co-channel guard distance as can be seen also from the Table 2.2.

The uplink interference in the white space base station means that the high power DTT transmitters cause co-channel or adjacent channel interference, blocking or overloading to the base station when it is in the receiving state. The adjacent channel interference, blocking and overloading are possible if the transmitter is in the near vicinity and possibly in the same mast with the DTT transmitter. The first adjacent channel interference is mitigated by the fact that white space base station has to be outside the TV contour and the TV transmitter emission mask attenuates the transmitted signal as described in the Table 2.3

Table 2.3 *The breakpoints for the non-critical DVB-T emission mask*

8 MHz channels	
Non-critical cases	
Relative frequency [MHz]	**Relative level [dB]**
–12	–77.2
–6	–52.2
–4.2	–40.2
–3.9	–0
+3.9	–0
+4.2	–40.2
6	–52.2
12	–77.2

In the second adjacent channel, interference from the DTT transmitter to the white space base station is possible. However, the white space base station has to be located near the DTT transmitter because in the second adjacent channel the attenuation only due to the DVB-T transmitters emission mask is 77.2 dB as can be seen from the Table 2.3.

Blocking and overloading depend on the distance to the DTT transmitter but also on the white space base station properties. These problems might be possible especially with devices designed for the whole 470-790 MHz band since the selectivity can suffer because of the wide operation region. The co-channel interference from the DTT transmitters is very likely due to the high effective antenna heights of the TV transmitters (300-500m.) and high transmission powers (80 dBm). With the base station antenna heights for example 50 – 100 m this can result in high co-channel interferences to many of the seemingly unoccupied channels in the region.

In the downlink direction CPE acts as a receiver and can be interfered by the DTT transmitters. Since the DTT network is designed for receiver heights of 10 m the co-channel and adjacent channel interferences are not very likely. Blocking and overloading on the other hand are possible. When using the second adjacent channel and operating near the DTT transmission mast, the DTT signal is strong enough to cause blocking or even overloading.

In the uplink direction the CPE is unlikely to cause co-channel interference. The guard distance of the base station is in most cases so large that it exceeds the CPE guard distance. Adjacent channel interference, blocking and overloading are however possible. This is due to the fact that the CPE antenna may be positioned in the near vicinity of the DTT receiver that is in the same roof perhaps with around 5 – 10 m distance to DTT receiver. In the Table 2.4 is presented all the mentioned interference cases in fixed white space network and fixed DTT receivers.

Table 2.4 *Summary of the different interference cases in fixed white space network*

Interferer	Victim	Reason	Importance
WS BS	DTT Rx	Co-channel	high
WS BS	DTT Rx	ACI	medium
WS BS	DTT Rx	Blocking	low
WS BS	DTT Rx	Overloading	low
DTT Tx	WS BS	Co-channel	high
DTT Tx	WS BS	ACI	medium
DTT Tx	WS BS	Blocking	medium
DTT Tx	WS BS	Overloading	low
WS CPE	DTT Rx	Co-channel	low
WS CPE	DTT Rx	ACI	high
WS CPE	DTT Rx	Blocking	high
WS CPE	DTT Rx	Overloading	high
DTT Tx	WS CPE	Co-channel	low
DTT Tx	WS CPE	ACI	low
DTT Tx	WS CPE	Blocking	medium
DTT Tx	WS CPE	Overloading	medium

The importance field in the Table 2.4 demonstrates how important the said interference scenario is in the planning of the network. High means the interference cases that are reasonable to calculate and evaluate in all cases. The illustration of the high interference cases is in the Figure 2.5.

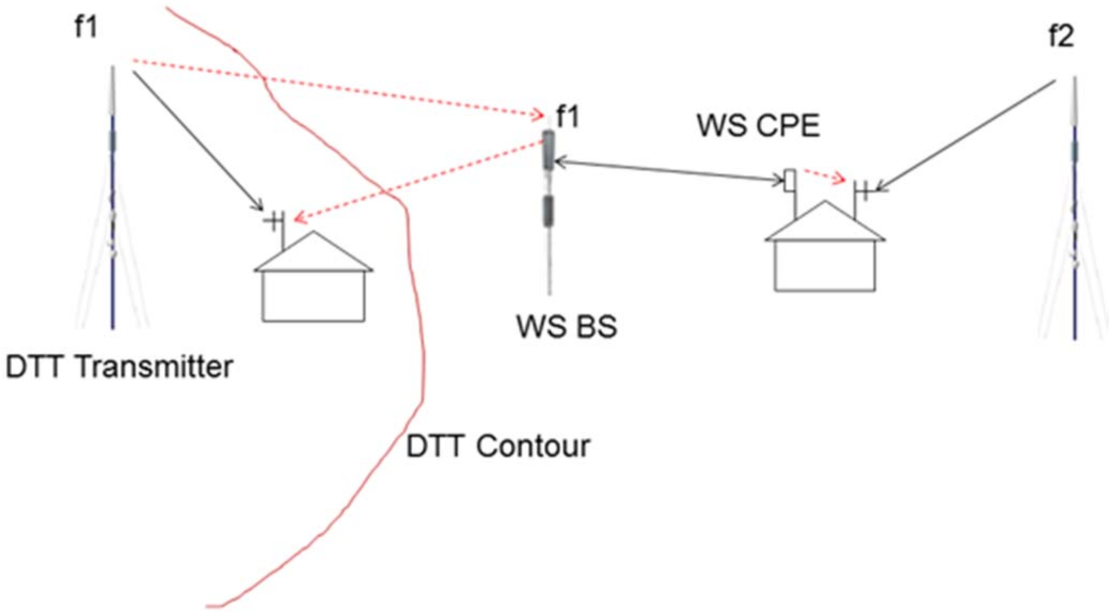

Figure 2.5 *The High importance interference cases in the fixed white space network assuming only the fixed DTT reception.*

All the other high importance interference cases are co-channel interferences, but the DTT receiver next to white space CPE can suffer from three different interference cases shown in the Figure 2.6.

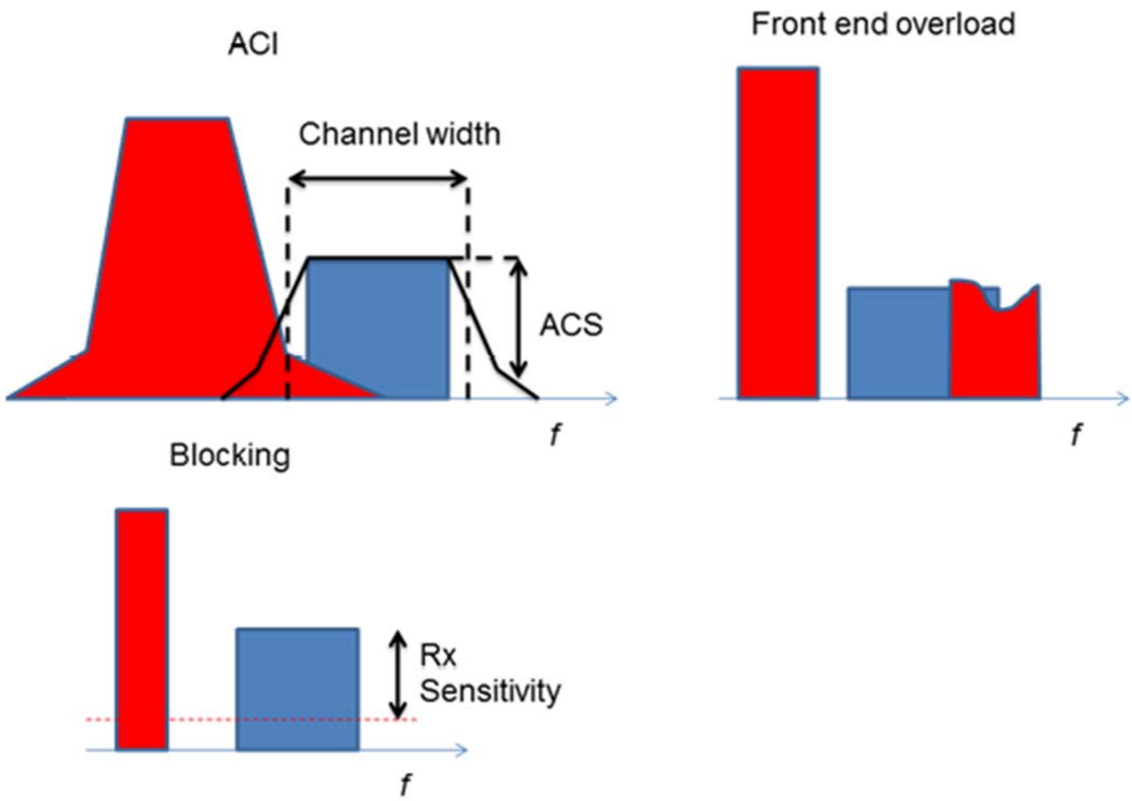

Figure 2.6 *Different interference cases for the DTT receiver near the white space CPE.*

Besides the high importance interference scenarios medium scenarios are the ones that are possible, but demands right kind of circumstances so to speak. Such scenario could be for example that white space base station is in the same mast with DTT transmitter. Low importance scenarios are ones that should not be possible if the regulations are obeyed.

3 WHITE SPACE RURAL BROADBAND PLANNING

The planning of the radio network depends on the type of the network. In this case the network is rural area fixed wireless broadband network. The goal in the radio network planning is to fulfill the requirements for coverage, capacity and quality while taking into account the radio propagation characteristic in the area [20]. The process comprehends making a link budget and calculating coverage by signal strength with proper propagation model based on used frequency, EIRP, base station and CPE antenna characteristics and antenna heights. One aspect of the frequency planning is also costs of the network. One reason to exploit the white space networks is that UHF band signals have good propagation characteristics and because the operation is unlicensed the costs could be so low that networks are profitable even in scarcely populated areas.

In the white space network planning there are some aspects that differ from other network planning. First of all the frequency planning is different since there is no fixed frequency band. The allowed EIRP can also vary depending on the situation and used frequency.

3.1 Frequency Planning

Frequency planning is the most important phase in the white space network planning. It determines whether the intended white space service is even possible in the wanted area. The intended service type, coverage and capacity, has a great impact on usable frequencies because of the needed antenna height and transmission power.

The rural broadband case uses the highest base station and CPE antenna height and power compared to other planned white space services at the moment. For this reason it can exploit the least of the free frequencies. First of all using the same frequency as the DTT transmission in the area is clearly out of the question. Based on the FCC and ECC proposals the usage of the first adjacent channels is not possible in rural broadband scenario. The second adjacent channel is usable according to the FCC. According to the ECC the frequency guard band could be even more than one adjacent channel depending on the transmission power of the WSD and the assumed DTT signal power in the area.

Second limiting factor is the frequency reuse that is how far the white space transceiver has to be from the contour where the co-channel is in use. This can be estimated by determining the maximum signal level for the white space signal in the co-channel contour edge. After that can be calculated the needed distance based on the used EIRP, frequency and antenna height and using proper propagation model. Safety distances have to be calculated also for the adjacent channels contours. The safety distances to adjacent channels' contours are much shorter due to the transmitters' adjacent channel attenuation. The principles of the frequency planning in downlink direction protecting DTT reception is shown in the Figure 3.1.

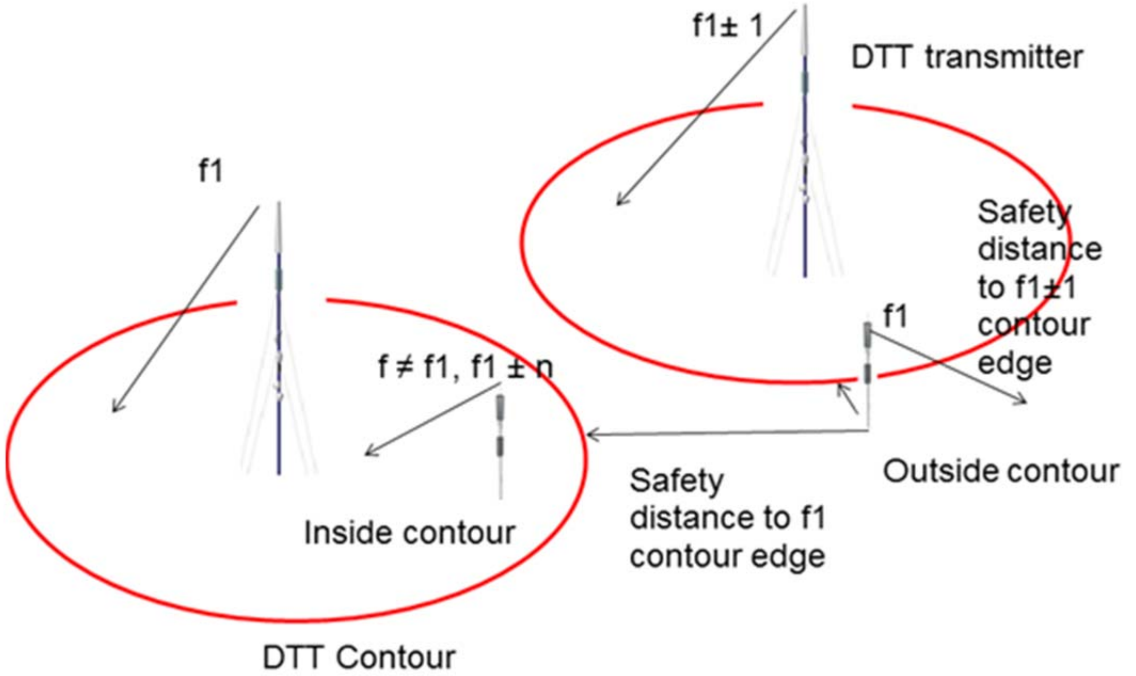

Figure 3.1 *The frequency planning in the downlink direction. Inside the contour sufficient frequency guard band has to be used (n marks the amount of adjacent channels). The FCC regulations propose value 1 for n, in the ECC proposal n depends on the white space base station parameters. Outside the contour sufficient safety distance has to be applied to the same channel contour as well as to the adjacent channels contours.*

The FCC proposal is using 14.4 km guard distance with 36 EIRP and 30 m antenna height. Taking I/N ratio of -20 dB as defined by the ECC the allowed signal strength in the 8 MHz band is -123 dBm. Because the white space base station is located outside the TV contour, an 5 dB antenna isolation can be assumed to the DTT receivers since the interfering signal comes from behind. For example, calculating the path loss for the white space base station with the ITU-R P.1546 model with time probability of 1% (worst case scenario), land path, frequency 630 MHz (middle point of the white space band), EIRP of 36 dBm and antenna height of 30 m. The sufficient interference signal strength of -123 dBm is obtained with guard distance of 30.1 km.

The use of the frequencies is also coordinated between the neighboring countries so when operating near the border these limitations have to be also considered. Other aspect limiting the usable frequencies besides protecting the DTT service is the interference in the channel. In the rural broadband scenario the goal is to cover possibly 10 km sector with broadband capacity. This requires low interference level on the channel so that sufficient C/I ratios can be achieved. In the rural broadband case the amount of so called good channels is the least. The important point is that in the white space operation the amount of usable channels depends on the intended service that is on the needed coverage and capacity. If using the white space frequencies to low power low height sensor networks, possibly almost all frequencies in the band can be used. Then for the rural broadband use, regionally there might not be usable frequencies at all.

3.2 Link Budget

After defining the usable frequency and transmission power the next step is defining the link budget. The radio link budget gives the maximum value how much the signal can attenuate before the receiver, that is, the maximum path loss. With the maximum path loss and the propagation model for the target area (urban, rural) the maximum coverage for the base station can be estimated. [20]

The link budget is system and usage dependent. In the rural broadband case the link budget is very simple because between the fixed antennas there are not so many factors to be taken in to account. Because the used system in this case is the fixed WiMAX, the link budget is presented accordingly.

First thing is to calculate the EIRP of the transmitter. The calculation of the EIRP begins with determining the available transmission power. After this comes the needed feeder length from which the cable loss can be calculated. Along with the cable losses there are connector losses that are losses due to reflecting power in cable connecting points. Besides losses there are also possible gains. Because in many cases the antenna does not radiate isotropically but concentrates most of the energy in certain direction, it has higher power density in that certain direction compared to isotropic radiator. When calculating EIRP this difference is taken into account by the means of antenna gain, which unit in this case is dBi. [21] Other gain can be for example amplifier, which connector losses have to be also included to calculations. According to [21], this gives us the equation for calculating the EIRP

$$EIRP = Tx\ Power - (feeder\ losses + connector\ losses + jumper\ lossess + (Tx\ antenna\ gain + other\ Tx\ gain) \tag{3.1}$$

In fixed antenna case the equation is the same for the downlink and uplink connection. [21] After determining the EIRP the next step is to calculate the receiver sensitivity. Receiver sensitivity consists in the simple case of thermal noise, the needed receiver SNR for the wanted capacity, the noise figure and the implementation loss. [21]

The needed receiver SNR depends on the used system. Basically there is certain thresholds for the different modulations for example Binary/Quadrature Phase Shift Keying (B/QPSK), 16 and 64 Quadrature Amplitude Modulation (QAM) and for the different coding rates for example (1/2, 3/4, 5/6). The coding rate tells the amount of data bits in relation to error coding bits, that is, ½ means that half of the bits are data bits and half is for error coding. The needed receiver SNR grows when increasing the used modulation and/or lowering coding rate [12]. The noise figure defines the receivers own noise, which constitutes from the receiver element's noise factors and gains, as introduced in Subsection 2.3. The first term has the most impact on the noise figure. In the receiver this is low noise amplifier. In practice the noise figure usually does not have to be calculated, it is provided by the manufacturer and could be something between 5-7 dB. [12] The implementation loss includes non-ideal receiver effects such as channel estimation errors, tracking errors, quantization errors, and phase noise. Basically implementation loss is the margin between theoretical needed receiver SNR and the practical values. Now the receiver sensitivity according to [21] can be calculated as follows:

$$Receiver\ sensitivity\ (Rs) = \\ thermal\ noise\ +\ Rx\ SNR\ +\ Rx\ Noise\ Figure\ +\ implementation\ losses \quad (3.2)$$

Last thing to add to calculations is different margins. Common margins are slow fading margin, fast fading margin, interference margin and building penetration loss. Simple propagation models calculate path loss only depending on distance, that is, all points on the circle around transmitter are assumed to have same path loss. There are however variations between these points due to shadowing. The effect of shadowing, also called log normal fading, is mitigated with log normal fading margin defined in [21] as:

$$lognormal\ fading\ margin\ =\ norminv(cell\ edge\ coverage\ propability, \\ mean\ of\ lognormal, standard\ deviation) \quad (3.3)$$

where *norminv* states for normal inverse cumulative distribution function. Fast fading margin is not needed when the receiver is not mobile. Interference margin can be very vital in the white space case because the co-channel interference is likely to occur from the distant TV transmitters especially to base station having antenna height around 100 m. Suitable values could be 2 dB to downlink connection and 3 dB for uplink [21]. Building penetration loss is not needed in the rural broadband case where the CPE antenna is assumed to be on the roof top. With all the previous information the simplified maximum allowed path loss for fixed wireless broadband is:

$$MAPLEIRP = \\ EIRP +\ CPE\ DL\ Rx\ Antenna\ gain\ + \\ CPE\ Rx\ -\ Rx\ sensitivity -\ lognormal\ fading\ marg. -\ interfer.marg. \quad (3.4)$$

The Equation (3.4) is for the downlink connection. In this kind of case the uplink is calculated with the same principle because the antennas are fixed. Only the EIRP and receiver sensitivity has to be calculated with uplink parameters.

3.3 Propagation Models

After estimating the maximum allowed path loss, the next step is to evaluate the coarse coverage. The maximum allowed path loss gives us the information about how much the path loss can be and propagation models are used to evaluate how far the signal can propagate with the allowed path loss.

An obvious starting point is to determine how much the signal attenuates in the free space. When propagating in free space the radio waves do not lose energy, at least in the distances of wireless links. It is however obvious that much of the energy is lost between antennas also in free space. The reason is that although almost all of the energy is present, it is expanded to wider area and receiver can capture only a small portion of this area. The free space can be depicted as homogenous area with no boundaries and radio wave propagates without obstacles. Propagating wave can be examined as sphere which expands from a point source outwards and the transferred energy of the waves is constant. The area of a sphere is $4\pi r^2$, where r is the distance between antennas. Power flux density of an isotropic antenna is as

$$\mathrm{S}(Pt, Gt, r) = \frac{P_t G_t}{4\pi r^2}, \tag{3.5}$$

where P_t is transmitted power and G_t is the transmitter antenna gain [22]. The received power is defined as

$$\mathrm{P_r}(\mathrm{A_e}, \mathrm{S}) = \mathrm{A_e} * \mathrm{S}, \tag{3.6}$$

where $\mathrm{A_e}$ is effective area of an antenna

$$\mathrm{A_e}(G_r, \lambda) = \frac{G_r \lambda^2}{4\pi} \tag{3.7}$$

where G_r is the antenna gain of the receiver and λ is the wavelength of the transmitted signal [23]. Substituting $\mathrm{A_e}$ and S in Equation (3.6) with Equations (3.7) and (3.5), results in following equation for received power $\mathrm{P_r}$.

$$\mathrm{P_r}(G_r, \lambda, P_t, r) = G_r * \frac{\lambda^2}{4*\pi} * G_t * \frac{P_t}{4*\pi*r^2}, \tag{3.8}$$

$$\mathrm{P_r}\,(G_r, G_t, \lambda, P_t, r) = G_r * G_t * P_t * \left(\frac{\lambda}{4*\pi*r}\right)^2, \tag{3.9}$$

Propagation loss is the relation between transmitted and received power [22]

$$\text{Path loss}(\mathrm{Pr}, Pt) = \frac{P_t}{\mathrm{P_r}}, \quad (3.10)$$

Using the Equation (3.10) and Equation (3.9) with isotropic antennas so that G_r, $G_t = 1$, free space loss can be written [22] as

$$\text{Free space loss}(\lambda, r) = \left(\frac{4\pi r}{\lambda}\right)^2, \quad (3.11)$$

Path loss is expressed in dB because it makes the calculations much easier, so expressing Equation (3.11) in logarithmic scale is:

$$\text{Free space loss}(f, d)[dB] = 32{,}4 + 20 * \log(f) + 20 * \log(d), \quad (3.12)$$

where f is frequency in MHz and d is distance in km [22]. The free space loss model is applicable only in the special case when there is line-of-sight and sufficient free area between the antennas. This area is called the Fresnel zone and if there are obstacles in or near vicinity the Fresnel zone, these have to be taken into account in the propagation calculations. This is because signals reflected from the obstacles in the first Fresnel zone have gone through a phase shift that causes destructive interference to the line-of-sight-signal. Fresnel zone is an ellipsoid which radius is defined as

$$F_n(\lambda, d_1, d_2) = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}, \quad (3.13)$$

where d_1 and d_2 are distances from transmitters in meters and n is the number of the zone and λ is the wavelength of the signal. The most important is the first Fresnel zone as depicted in the Figure 3.2. [24]

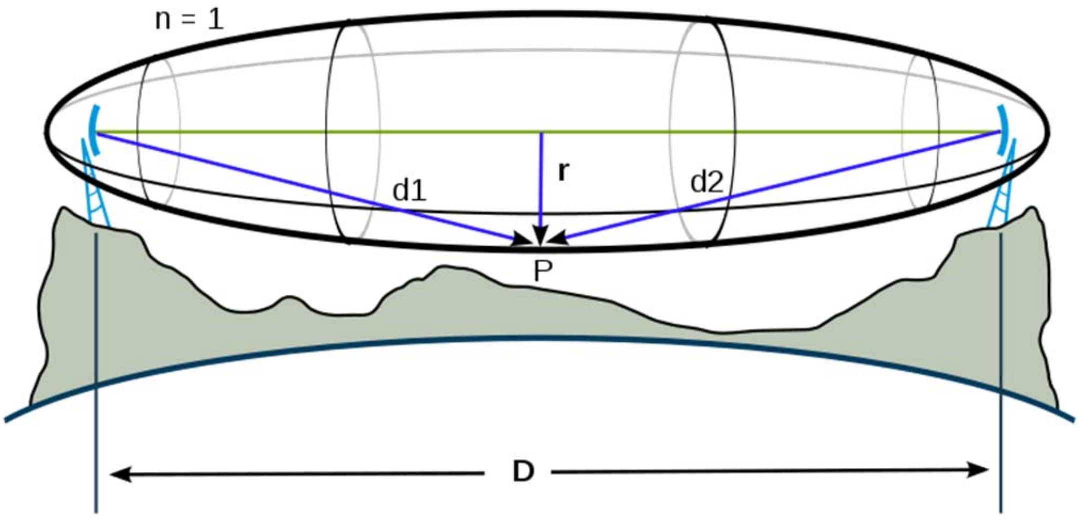

Figure 3.2 *The First Fresnel zone*

In most of the cases there are obstacles in the first Fresnel zone and different propagation model has to be used.

In addition to free space loss there are other calculation methods for determining electric field magnitude in certain points. These calculation methods can take into account the effects of the obstacles, shadowing and multipath propagation. In practice making exact calculations is not however possible or it is too time consuming. In the case of mobile CPE the exact calculations are impossible since there are infinite amount of possible signal paths. In fixed link the calculation is usually too complex and all the obstacles in the path has to be known. This is why empirical path loss models are used. Empirical models are made first of all by completing an extensive set of actual path loss measurements. Then an appropriate function is derived to match the measurement results, with parameters derived for the particular environment, frequency and antenna heights so as to minimize the error between the model and the measurements. One important factor is that each measurement represents a local mean that is averaged from several samples from a small area (around 10 – 50 m.) to remove the effects of the fast fading. One widely used fully empirical model is the Okumura-Hata model. [22]

The Okumura-Hata model is based on extensive series of measurements made in and around Tokyo city with frequencies between 200 MHz and 2 GHz. The model is not based on physical model, that is, predictions are made by approximating the most important graphs. The model includes different predictions for three different types of areas. The areas are distinguished by clutter and terrain categories and are named as open, suburban and urban. Open area is an open space with no tall trees or buildings in path, for example farmland with open fields and low buildings. Suburban area is a village or highway scattered with trees and houses. Urban is built up city or large town with large buildings and houses and tall, thickly grown trees. The urban areas model is taken as a reference and applied correction factors for conversion to the other classifications. The equations for the approximations according to [22] are

Urban area $\mathrm{L} = \mathrm{A} + \mathrm{B}\log\mathrm{R} - \mathrm{E}$, dB (3.14)

Suburban areas $\mathrm{L} = \mathrm{A} + \mathrm{B}\log\mathrm{R} - \mathrm{C}$, dB (3.15)

Open areas $\mathrm{L} = \mathrm{A} + \mathrm{B}\log\mathrm{R} - \mathrm{D}$, dB (3.16)

where

$$\mathrm{A}(f, h_b) = 69.55 + 26.16 * \log(f) - 13.82 * \log(h_b), \quad (3.17)$$

$$\mathrm{B}(\mathrm{h_b}) = 44.9 - 6.55 * \log(h_b), \quad (3.18)$$

$$\mathrm{C}(f) = 2 * (\log(\frac{f}{28}))^2 + 5.4, \quad (3.19)$$

$$\mathrm{D}(f) = 4.78 * (\log(f))^2 - 18.33 * \log(f) + 40.94, \quad (3.20)$$

$\mathrm{E}(h_m) = 3.2 * (\log((11.75 * h_m)))^2 - 4.97$, for large cities $f \geq 300$ MHz (3.21)

$\mathrm{E}(h_m) = 8.29 * (\log(1.54 * h_m))^2 - 1.1$, for large cities $f < 300$ MHz (3.22)

$\mathrm{E}(f, h_m) = \big(1.1 * \log(f) - 0.7\big) * h_m - (1.56 * \log(f) - 0.8)$, for medium to small cities (3.23)

where h_b is the height of the base station in meters and h_m is the height of the mobile in meters. The model is valid only for 150 MHz $\leq f \leq$ 1500 MHz, 30 m $\leq h_b \leq$ 200 m, 1m < h_m < 10 m and R > 1 km. The path loss exponent is B/10, which is a little less than 4 and it decreases when the base antenna height increases. [22]

International Telecommunications Union (ITU) is responsible for allocation of radio spectrum and satellite orbits. Besides this it also provides recommendations for suitable propagation models. Vast amount of different models makes selection of the suitable model difficult and so ITU provides recommendations for suitable models. Although there would be more accurate model available for the situation the ITU recommendations are widely accepted and provide good reference and can be used for coordination and comparison purposes.

The ITU-R P.1546 provides radio propagation predictions for point-to-area terrestrial services in the frequency area of 30-3000 MHz. The distance is from 1 km to even 1000 km and effective antenna height less than 3000 m. The model is empirical and interpolated/extrapolated from field strength curves as function of distance, antenna height, frequency and percentage time. [22] This is widely used for TV transmitter coverage calculations, but is also usable for fixed broadband connections. It is also good in the white space case because the white space signal strengths are compared to TV signal strength for which the ITU-R P.1546 is also used. The graphs provided by ITU can be used as it is for predictions, but it is intended that computer implementations will use the tabulated field strengths available from the Radiocommunication bureau. Example of field strength graph can be found in document [25]. In this thesis the ITU-R P.1546 is used in Atoll planning tool and also in Matlab. The Matlab script folder can be downloaded from Matlab central:
http://www.mathworks.se/matlabcentral/fileexchange/25099-itu-r-p-1546-calculator.

3.4 Antennas

To transmit or receive electromagnetic wave an antenna is needed. Antenna is an element that converts the electrical energy travelling along a transmission path into electromagnetic waves in space. The changing current in a conductor produces changing magnetic field around it. Changing magnetic field produces changing electric field and changing electric field produces once again changing magnetic field and so on. [24]

These changing fields carry the electric charges over the air and when a conductor is put to this changing electric field it starts to conduct these charges and that is how the electromagnetic wave in space is conducted back to electrical energy that goes to receiver. It is clear that for most solutions just to produce an electric field of some kind is not good enough. The most important parameter in the design of antenna system is antenna gain. The antennas are passive devices and the power radiated by the antenna cannot be greater than the power inducted from the transmitter. The power from the transmitter can be however concentrated to certain direction and antenna gain is the gained advance of this power concentration compared either to isotropic radiator or half-wave dipole. A high gain is achieved by increasing the aperture area A, of the antenna. The amount of power captured by the antenna is given as

$$P(p, A) = p * A, \tag{3.24}$$

where p is the power density and A is aperture area of the antenna [23]. Antennas obey reciprocity and so the transmit and receive gain is the same and antenna does not have to be considered indifferently depending on the operation. When the antenna gain is described compared to isotropic radiator, it is called effective isotropic radiated power (EIRP) and the gain is expressed in dBi units. When it is compared to half-wave dipole the gain is called effective radiated power (ERP) and expressed in dBd. The relation between these two is as [22]:

$$EIRP[dB] = ERP + 2.15, \tag{3.25}$$

Antenna gain expresses the maximum gain difference compared to isotropic or half-wave dipole. It decreases when the wanted radiation beam width is increased. The radiation of the antenna cannot be completely limited to the direction of the intended beam width. The attenuation the antenna produces to all directions is expressed in antenna pattern. [22] The antenna pattern is expressed in decibels and in the direction of the maximum antenna gain the attenuation is zero dB's and the attenuations to the other directions are expressed related to this. The antenna beam width is the sector where attenuation is below three dB's. Antenna patterns are often described as vertical and horizontal. Antenna patterns are cross section from the actual 3D beam. Horizontal pattern is the one that shows in the planning tool and in some cases vertical patterns of the antennas are not even provided.

4 STANDARDS AND TECHNOLOGIES

Standards for the WSD's are still under development. The operational features of the WSD depend on the application it is targeted at and so different applications demand different standardization. If some white space application becomes widely used, then using certain standard for that application is likely to ease the interoperability. In the applications that are used only in some special cases, the used standards may vary and also proprietary solutions may be used.

This chapter introduces three different standards. The 802.11af standard is meant for white space WLAN solutions. The 802.22 is targeted to the white space rural broadband applications and then the Weightless is for Machine-to-Machine (M2M) applications. From the technologies WiMAX is introduced, although it is not designed for white space operation, but because for practical reasons WiMAX devices tuned to UHF band are used in this pilot. Few devices specially meant for white space operation are also already on the market and two of them, NEUL and Carlsson Wireless are presented briefly in this Chapter.

4.1 802.11af

The 802.11af standard is still under development at the moment and specific details for physical and medium access layers are not published yet. What is known, is that as the code implies the standard is related WLAN and it is widely called the white Wi-Fi. It should be noted that the term Wi-Fi can be misleading in this contexts. For this reason the Wi-Fi alliance has prohibited the use of the term white Wi-Fi, because the Wi-Fi consortium is not participating in the development of the white space WLAN. Also there is not any interoperability with the official Wi-Fi devices.

In general the idea is to make WLAN that uses cognitive radios and the white space spectrum. The standard will be based on FCC regulation concerning the use of the database for ensuring that unlicensed devices do not interfere with licensed users. Low power fixed devices will be required to register their location, channel of operation and transmit power in a geo-location database. This information is also available for other white space devices to enable channel and power selections for optimal coexistence. Transmit power control is also demanded in regulations and the goal in 802.11af is to make it so that the used power is sufficient for robust communication, but does not exceed that. FCC regulations do not cover the interference between white space devices. In the 802.11af the intention is to use collision sensing multiple access with collision avoidance, as used in earlier 802.11 standards with same thresholds for sensing. [26]

4.2 802.22

The 802.22 standard is targeted to be used for the rural and remote area wireless broadband access. It is assumed that good propagation characteristics of the UHF band combined with unlicensed operation enables large base station coverage and cheap implementation. This could result in providing broadband access to even sparsely populated area with low cost.

The network topology defined in 802.22 is that there are fixed wireless point-to-multipoint connections. A base station manages its own cell and all the CPE's inside the cell coverage area. In addition to traditional role of the base station it also manages distributed sensing which is a unique feature compared to existing networks. The base station instructs various CPE's to perform distributed measurements of different TV channels. Based on the results the BS can take actions to protect incumbent services if needed.

The capacity of the 802.22 system is defined as between 0.5 bit/sec/Hz and 5 bit/sec/Hz. With average 3 bit/sec/Hz in 6 MHz band this would mean PHY data rate of 18 Mbps in the downlink direction for one base station. The system is considered to have 12 simultaneous users so in the coverage edge this would mean 1.5 Mbps in downlink. In the uplink peak throughput of 384 kbps is specified. The idea of the 802.22 system is to have large coverage to be able to cover rural areas with low cost. Even 100 km coverage per cell has been proposed, but current specified coverage range is 33 km using the 4 watts EIRP for CPE [27]. The standard is already published, but at the moment it is not considered to become widely adopted. This is mainly because the network bit rates defined in the standard are considered to be relatively low.

4.3 Weightless

The Weightless Standards-SIG (S-SIG) is a special interest group set up within Cambridge Wireless. The purpose is to develop a standard for the machine-to-machine technology operating in the white space spectrum. Originally the draft of the Weightless specification was provided by Neul. The goal of the S-SIG is to develop this draft version to the point that specification can be used by any interested party for equipment production.

There are several features in Weightless that are meant to meet the requirements of the M2M market. First of all the technology is supposed to be very low cost and possible to be readily integrated into machines. Secondly very low power consumption so that battery life could be years. This is important for applications where the WSD's are in places that are hard to access. And lastly the ability to efficiently handle large networks with lots of chips or "subscribers". And as a consequence from previous demand, the network has to be able to handle large numbers of small data packets efficiently. In this kind of scenario there is also need to use small and simple antenna at the receiver, which is not trivial with wavelengths of the white space frequencies. Finally, also these devices have to have also the same cognitive capabilities and robustness for interference as the other white space devices. [28]

As a design overview there is purpose to make flexibility in the provided data rate depending on the application, range and environment. The duplex mode is Time Division Duplex (TDD) since there is no defined uplink and downlink in the white space spectrum. Already well known and much used frequency hopping is utilized to avoid inter system and outer system interferences. [28] The network determines the frequency hopping pattern given the available channels. Frequency hopping occurs at the MAC frame rate, so both the downlink and uplink sections of a given MAC frame use the same channel [29]. Weightless includes also variable spreading factor from one to 1024 to provide processing gain to increase range or enable low power. The traffic is designed to be highly asymmetric and used powers differ greatly in base station and devices. This results in substantial differences and complexity between base station and devices.

On the physical layer the downlink and uplink use different multiple access scheme. Single carrier and time division multiple access is used in the downlink so that the whole bandwidth is reserved for single terminal at a given time. Uplink uses frequency division multiple access with 24 sub-channels. The reason for this is that it reduces the noise floor at the base station receiver and so balances link budget. On the other hand it allows multiple terminals to transmit simultaneously [29]. There is also alternative uplink configuration that uses sub-channels with a comb structure to meet the US regulatory.

On the medium access layer there is repeating frame structure in two second intervals, it takes one second for device to entirely synchronize. Downlink frame is flexible, uplink is boundary. Also periodical broadcast frame is used to notify all terminals of control information, such as forthcoming change of hopping sequence. [28]

4.4 WiMAX

A broad industry consortium, the WiMAX forum was developed with intention to make standards-based interoperable solution for fixed wireless broadband. Later it was decided to add the support for the mobile use. The standards are from the 802.16 standard family and there are three of them. The first one was completed in 2001 and was focused on the point-to-multipoint fixed line of sight connections using 10-66 GHz. The next standard called 802.16-2004, had several additions including fixed non-line-of-sight connections and new frequency range (2-11 GHz). Several bandwidth options starting from 1.75 MHz, use of Orthogonal Frequency Division Multiple Access (OFDMA) and lower gross data rate from 1 – 134.4 Mbps. The WiMAX has also features from third standard 802.16e-2005 and most prominent addition is the mobile non-line-of sight connection and also overall system capacity and spectral efficiency improvement by adding Multiple Input Multiple Output (MIMO) support.

The actual physical layer of the WiMAX is a combination of these two standards with some of the features defined as optional and some mandatory. There are several different profiles for both fixed and mobile scenarios. The basic physical layer structure is OFDMA with either TDD or Frequency Division Duplex (FDD). TDD is preferred and FDD is meant to be used only in a situation that for example regulatory demands use of separate uplink and downlink channels. The physical layer is also very flexible with adaptive modulation and coding. The medium access control (MAC) layer is defined also in the standard and it uses MAC protocol data units to take the packets from the upper layer and organizes the data for transmission over the air. The standard has a MAC convergence sub-layer that can interface with many different higher layer protocols. In WiMAX however, it was decided to choose only Ethernet and Internet Protocol support. [30]

4.5 Neul

The NeulNET transmitter has been specifically designed to occupy one single Television White Space (TVWS) channel. In practice this demands to fulfill the very stringent FCC spectral mask. NeulNET claims to have reached this demand by the means of single carrier modulation. Most of the systems today use the multicarrier modulation and especially Orthogonal Frequency Division Multiplex (OFDM). OFDM has some downsides when it comes to the spectrum shape. First of all the OFDM spectrum cannot be filtered too tightly because of the risk of losing signal integrity. Besides this, OFDM has high Peak to Average power Ratio (PAPR) due to carrier peaks. Power amplifiers do not have sufficiently wide linear region for this and the operation in the non-linear region causes unwanted spectral re-growth.

The devices can use either 6 MHz or 8 MHz channel bandwidth depending on the channel width used in the target location. The devices have built-in global positioning system radio enabling satellite positioning so that the location of the device can be informed to the database. Neul also maintains own TVWS database that devices are configured to access for determining free channels. Frequency hopping is used in the free channels to avoid interference to other systems and also to enhance the connectivity in the varying conditions. MIMO technique is used to deal with the co-channel interference that is general in the TV spectrum. [31]

4.6 Carlsson Wireless

Carlsson wireless is another device manufacturer with the focus on white space operation. Especially the emphasis is on the rural broadband, but also devices have also features suitable for machine to machine applications. The emission mask is claimed to meet the FCC regulation. The devices can have bandwidth from 100 kHz to 4.5 MHz with 8 MHz or 6 MHz spacing depending on used TV channel width. The frequency range is from 470-786 MHz.

Carlsson Wirelesses base stations utilize MIMO technique to mitigate the effect of co-channel interference but CPE’s use single input single output, that is, only one antenna is used. Duplex mode can be FDD in point-point connections but otherwise TDD is used. [32]

5 PLANNING THE DOWNLINK COVERAGE FOR THE KIRKKONUMMI PILOT CASE

The wireless broadband pilot case was proposed by a network operator, which could provide an Internet access to three locations near Kirkkonummi. Digita is the provider of the infrastructure and the network planning. The main goal was to study, could these kinds of applications be possible with the WiMAX devices used in the white space band. The technical details of the used Airspan MicroMax devises can be found in [33]. It was important also to provide information about the rural broadband scenario to all participants in the project.

It was decided to try if the Digitas Espoo's radio and television transmission mast could be used for the base station antenna. The high power digital television transmitter operates also on the same mast which brings it own challenges to the implementation.

5.1 Locations

The intended pilot locations are depicted in the Figure 5.1. The transmission mast is in the top corner on the right.

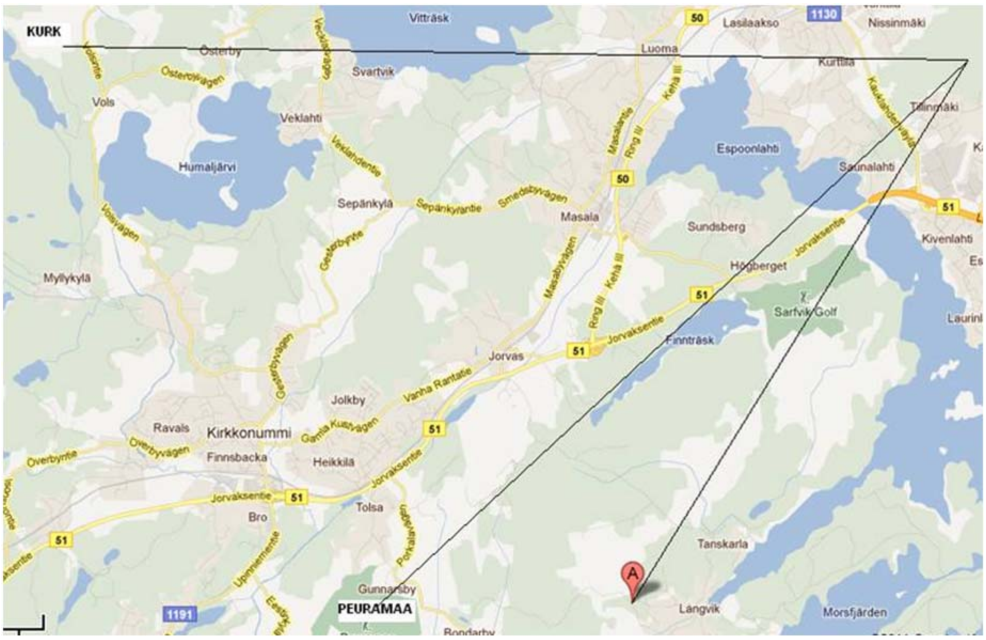

Figure 5.1 *Pilot locations*

Exact distances and directions for the locations starting from the right are:

- Location one: Honskby 10 km 214° from the mast (0° corresponds to north)
- Location two: Peuramaa 13 km 228° from the mast
- Location three: Kurk 14 km 275° from the mast

5.2 Downlink Frequency Plan

The frequency plan was in a way made easier in this case by the limitations of the air span WiMAX devices which can operate only on UHF channels 50-55. The down side of this is not to be able to use the best channel over the whole UHF DTT band.

Because the channels 53 and 52 are in use in Espoo transmitter it was clear that channels 51, 52, 53 and 54 were not usable, because of the limitations on operating in co-channel or first adjacent channels. With the possible options narrowed down to channel 50 and 55 the decision was made based on distance and direction to co-channel DTT contour. Direction is meaningful in this case since the base station antenna was directional with 61° beamwidth so the interference to directions outside the antenna beamwidth is attenuated.

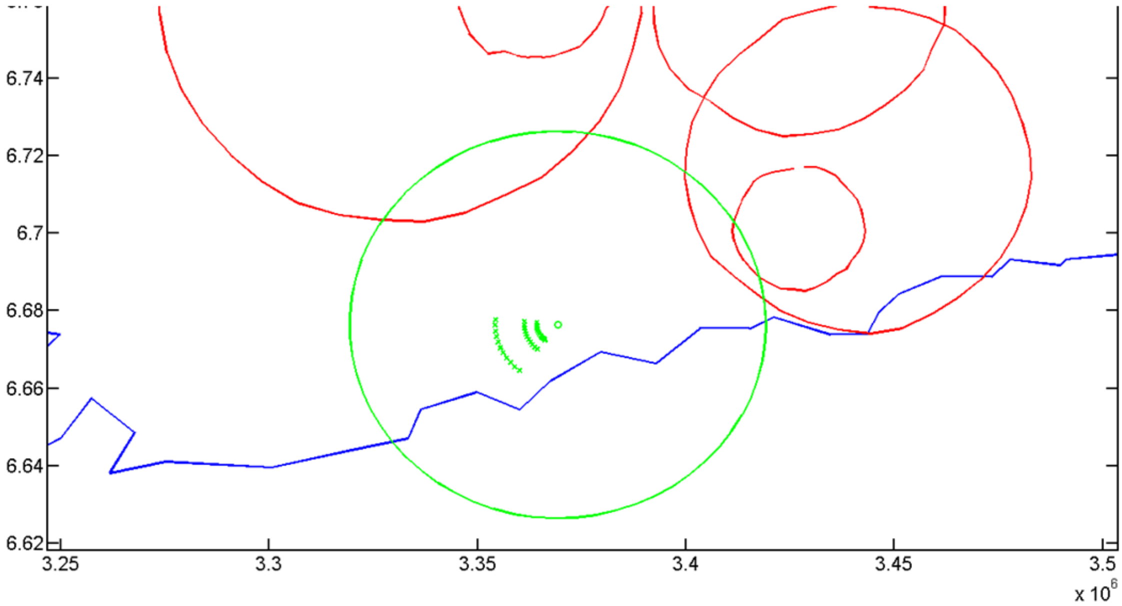

Figure 5.2 *Channel 50 DTT contours with 95% location probability in red and the green dot is the BS, green x's mark the width and direction of the BS transmission and green circle is 50 km radius for distance estimation. Blue line is Finland's coast line.*

Figure 5.2 shows the closest co-channel DTT contours in red. Green circle is meant to help in the evaluation of the distances and the radius of the green circle is 50 km. The transmission beamwidth and distance (15 km) is marked with green x.

From the figure we can see that there is no risk of causing interference to DTT receivers. A simple calculation can be also made to verify the low probability for co-channel interference to DTT network. The closest DTT contour is approximately located 35 km away 340° from the mast. The antenna pattern of the intended UHF antenna is introduced in Figure 5.3.

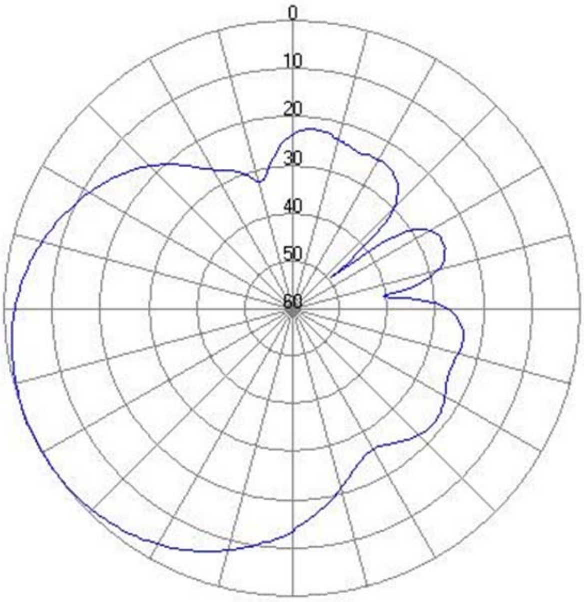

Figure 5.3 *The Espoo antenna pattern*

Now as it shows in the antenna pattern the direction 340° has attenuation of about 30 dB. Assuming an EIRP of 36 dBi the transmission power is 6 dBm to the direction of the contour. Calculating with the free space loss as introduced in the Equation (3.12) the 35 km distance with the 706 MHz frequency results in the path loss of 120 dB. If also assuming 5 dB back lobe attenuation from the DTT receiver, the interference power becomes 6 dBm – 120 dB – 5 dB = -119 dBm.

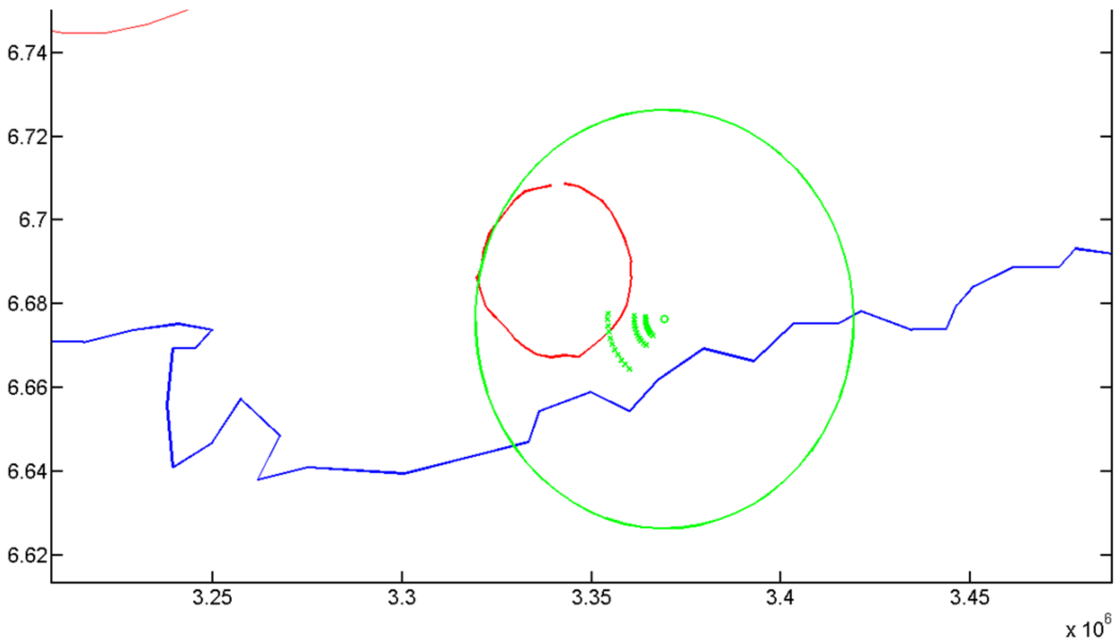

Figure 5.4 *Plot of the channel 55 with the same color map as in the previous picture.*

From the Figure 5.4 of the channel 55, we can see that there is a lower power DTT station nearby. The whole contour is within the 50 km radius and the station is located in such a direction that interference is possible to the DTT receivers.

It is clear that channel 50 should be chosen in this scenario. When operating close to the borders also neighboring countries has to be taken into account. In this case the use of channel 55 is limited due to Russia so channel 50 is the only option.

A Matlab function was also made to calculate the free channels based on the interference to the DTT receivers in general case when the base station could use all the channels in the 470 – 790 MHz band. The channels are determined free, based on the sufficient frequency and distance separation so that no interference should be caused to the DTT network. Since there is a not yet finalized regulation in Europe, some kind of combination of the FCC and the ECC regulations is used. In the following results, frequency separation of one guard channel is used. A separation distance of 54.7 km is used for the co-channel (calculated in the same manner as in the Subsection 3.1) and 2.6 km for the adjacent channel. In the adjacent channel calculation the WiMAX spectral mask was applied [30].

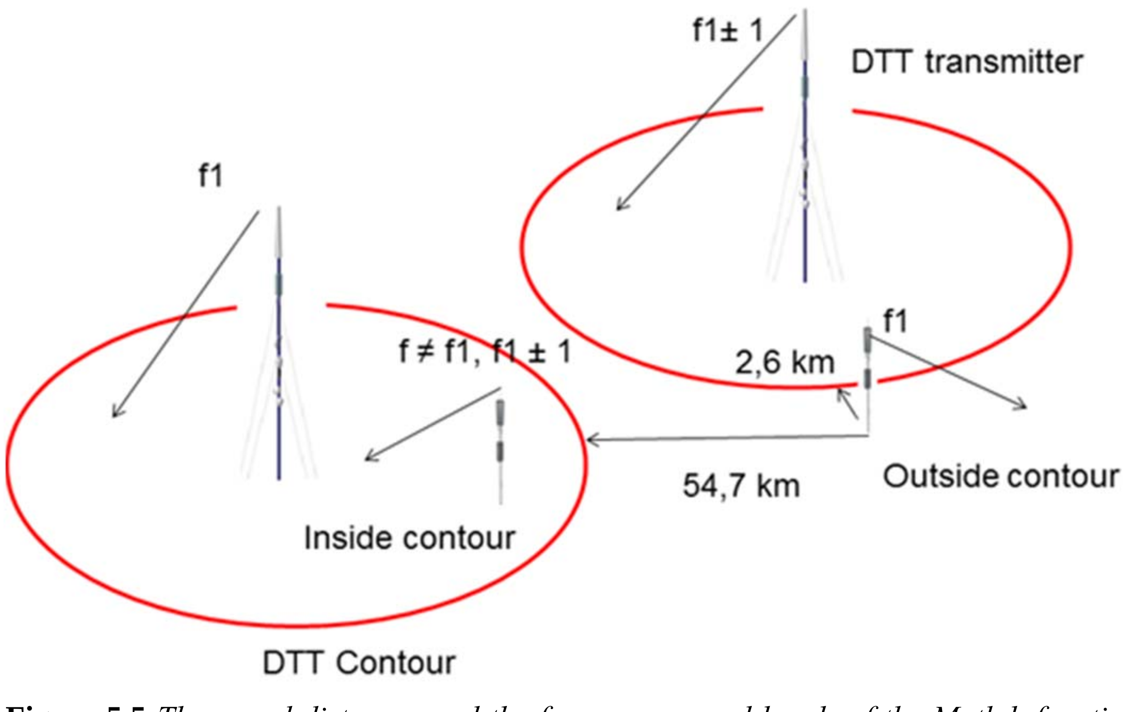

Figure 5.5 *The guard distances and the frequency guard bands of the Matlab function used for calculating the free channels based on the interference to the DTT network.*

With these limitations and considering only the Finnish transmitters, the usable channels would be 30, 37 and 38. The amount of the channels is quite small to say the least. What is interesting is that the channel 50 used in the pilot would not be usable with this criteria. This calculation does not take into consideration any eased demands if operating in the same mast with the DTT transmitter. As in reality causing interference to the DTT network is highly unlikely in the area of a very strong DTT signal. Some comparison with this calculation, of the usable channels in Espoo, is done in the Subsection 7.1 from the channel conditions point of view.

5.3 Link Budget

The link budget is based on an earlier link budget made for Jokela measurements documented in [34]. Now the base station antenna is located higher and so the cable loss is increased due to the longer cable. The antenna element is also different with a higher gain in this case.

Some other changes were made as well based on [21] and [30]. The values in the Jokela link budget were only estimates based on other known systems. Also it seems that the allowed path calculation does not include receiver antenna gain which increases the Maximum Allowed Pathloss (MAPL). The link budget for Jokela case ended up with a MAPL of 110.34 dB. The Table 5.1 shows the link budget for the Kirkkonummi case.

Table 5.1 *The WiMAX link budget for the Kirkkonummi case.*

Wimax DL Link-budget	
Tx Power (dBm)	27
Cable loss	7,93
Tx antenna Gain (dBi)	18,75
EIRP (dBm)	37,82
Frequency (MHz)	706
wavelength (m)	0,424929
Rx Antenna Gain (dBi)	10,5
Bandwith (MHz)	5
Rx NoiseTemperature (K)	300
Rx Noise (dBm)	-106,84
Noise Figure (dBm)	7
Implementation Loss (dB)	2
Required SNR 16-QAM 1/2 (dB)	10,5
Receiver Sensitivity (dBm)	-87,34
Desired User Margin (dB)	10
Maximum Allowed path loss (dE	125,66

Changes that were made to the reference link budget were that the implementation loss is changed from five decibels to two decibels and the required SNR is dropped from 11.5 to 10.5 dB according to [21]. This drops the receiver sensitivity four decibels to -87.34 dBm. Taking account the receiver antenna gain, the MAPL then becomes 125.66 dB, which is approximately 15 dB more than in the reference link budget.

The receiver sensitivity of the WiMAX devices was also verified by measurements performed in the radio laboratory in the Turku University of applied sciences. In the measurements there were adjustable attenuators between the base station and CPE and attenuation was increased in one decibel steps from 120.75 dB until the link failed. The link parameters for every attenuation value were written down from the configuration software of the devices. Some example values are presented in the Table 5.2.

Table 5.2 *The link measurements for the WiMAX system.*

Path loss	DL RSSI	Effect. SNR	DL Mod.	UL RSSI	UL Power	Effect. SNR	UL Mod.
120,75	-70,2	28,6	64QAM 3/4	-70	24	26	16QAM 3/4
123,75	-73,6	27	64QAM3/4	-70	26	24	16QAM 3/4
125,75	-75,6	24,6	64QAM3/4	-70	25	24	16QAM 1/2
127,75	-76,4	23	64QAM 2/3	-70	25	23	16QAM 1/2
130,75	-80,2	19,8	16QAM3/4	-70	26	23	QPSK 3/4
133,75	-83,2	17	16QAM 1/2	-91	26	10	QPSK 1/2
138,75	-88	11,8	QPSK 1/2		26		BPSK 1/2

According to the measurements the WiMAX link can have greater path loss than the link budget estimation gives. Comparing the estimated MAPL for 16-QAM ½ which was 125.66 dB to MPL value for 16-QAM ½ in the lab test which was 134.75 dB, there is 7 dB difference. This is a good thing and gives confidence that planned sites can be covered. One reason for difference between the estimation and the measured values is that estimation is meant for coarse coverage planning and has some margins so that results would not be too optimistic.

5.4 Coverage

The actual signal strength estimations were done on a network planning tool Atoll. The Atoll had been used already in the Jokela and Helsinki test cases and so the same system parameters were used also in this case. Also there is some comparison between the path loss predicted by the Atoll using the ITU-R P.1546 (with time and location probability 50%) and the Okumura-Hata model. Since the magnitude of the electric field strength varies over time some models have the time probability parameter. In the ITU-R P.1546 model the time probability can be chosen between 1 – 50 % and it means that the electric field strength is more than estimated selected percent of time. The propagation calculations done with network planning tools are made with selected pixel size. For example with 20 m pixel sixe a 40 m^2 area has the same estimated electric field strength. Inside the pixel there might be variations in the electric field strength so location probability is used. The whole area is estimated to have the certain best electric field strength, if percentage of the area defined in location probability, has this electric field strength.

Before going further with the building of the links, some calculations were needed to estimate if the scenario was executable. For the first calculations two different antenna heights were used, namely 90 and 120 meters, according to what could be used in the Espoo TV mast. The effective antenna heigth was about 40 m more than the antenna height since the mast is located on top of a small hill. Also it was estimated that about 20 m cable would be needed in addition to antenna height in the base station end to reach the base station. The Table 5.3 lists all the other used parameters in the prediction for antenna height of 90 m.

Table 5.3 *EIRP for the 90 m. base station antenna height*

Basestation antenna gain AT15-250 X 706	18,75	dBi
Transmission power	28	dBm
Cable loss 7/8" 110m	3,75	dB
Cable loss ½" 0,5 m.	0,3	dB
Miscellaneous loss	3	dB
Sum losses	7,05	dB
EIRP	39,7	dBm

The Table 5.4 shows the same parameters with antenna height of 120 m. The EIRP reduces because of the longer cable length, but the higher antenna may still have better coverage.

Table 5.4 *EIRP for the 120 m. base station antenna height*

Basestation antenna gain AT15-250 X 706	18,75	dBi
Transmission power	28	dBm
Cable loss 7/8" 140m	4,77	dB
Cable loss ½" 0,5 m.	0,3	dB
Miscellaneous loss	3	dB
Sum losses	8,07	dB
EIRP	38,68	dBm

The Table 5.5 contains the parameters for the CPE receiving end.

Table 5.5 *The CPE parameters*

CPE antenna gain Omni UHF	10,5	dBi
CPE antenna height	10	m
Losses	2	dB

Since the angle difference between the first and the third location was 275°-214° = 61° the plan was to cover all the locations with one antenna direction. The planned antenna had beam width of 61° which is sufficient, but in the limit. The Table 5.6 presents the estimated downlink Receiver Signal Strength Indication (RSSI) and path loss for the antenna height of 90 m and antenna direction 243°.

Table 5.6 *The estimated DL RSSI and the path loss for the 90 m. antenna height*

Location	DL RSSI [dBm]	Path loss [dB]
1.	-79,77	128,07
2.	-83,08	131,38
3.	-87,69	135,99

The Table 5.7 shows the estimated RSSI and the path loss for the 120 m antenna. It can be seen that the higher antenna actually gives better coverage despite the increased cable loss.

Table 5.7 *The estimated DL RSSI and the path loss for the 120 m. antenna height.*

Location	DL RSSI [dBm]	Path loss [dB]
1.	-78,79	126,09
2.	-81,75	129,05
3.	-85,6	132,9

The Table 5.6 and the Table 5.7 shows that when comparing to the measured link budget, even with the higher antenna height the estimated signal strength in the third location is only about 2 dB higher than the maximum receiver sensitivity found in the laboratory tests. After these results decision was made not to cover the location three, because of the too long distance. The antenna was directed towards the second location because it needed all the possible gain and the first location would be also sufficiently covered. At this point the antenna installation plan was ready and the antenna height became 106 m and the cable length was approximated to be 130 m. In the Table 5.8 there is the EIRP for the actual antenna height and the cable length.

Table 5.8 *EIRP with 106 m. antenna height and 130 m. cable.*

Basestation antenna gain AT15-250 X 706	18,75	dBi
Transmission power	28	dBm
Cable loss 7/8" 130m	4,32	dB
Cable loss ½" 0,5 m.	0,3	dB
Miscellaneous loss	3	dB
Sum losses	7,62	dB
EIRP	39,13	dBm

The Table 5.9 introduces the estimated the DL RSSI and the path loss for the two locations. The antenna direction is now toward the second location that is 228°.

Table 5.9 *The DL RSSI and the path loss for the 106 m. antenna height.*

Location	DL RSSI [dBm]	Path loss [dB]
1.	-77,25	124,88
2.	-81,8	129,43

The Table 5.9 shows that margins for the connection are very narrow. Comparing to the laboratory measurements shown in the Table 5.2, connection should be possible to the both locations but the real signal strength may differ several decibels from the estimated. However, it was decided to try if the connection would be possible since the white space rural broadband should be able to have this kind of coverage in order to be interesting commercially. The Figure 5.6 shows the downlink coverage of the planned network.

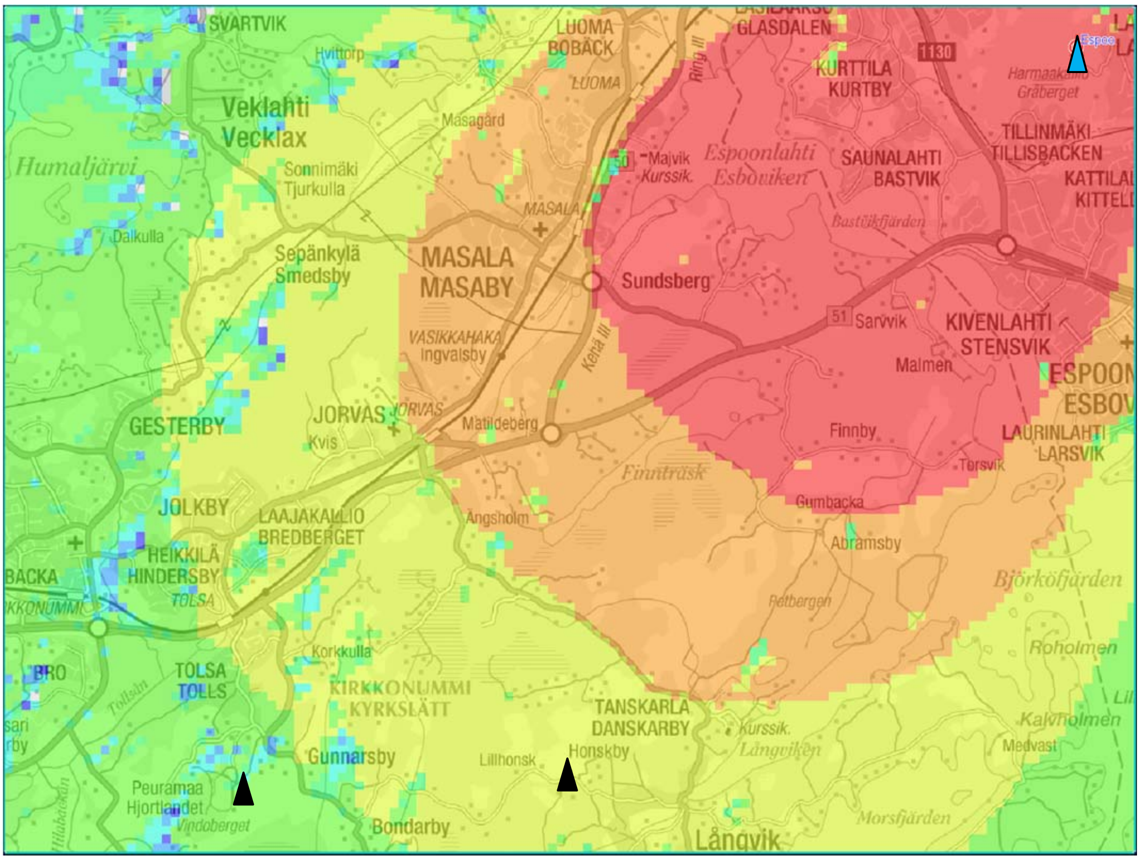

Figure 5.6 *Downlink coverage of the Espoo network estimated with Atoll. The planned sites are marked with black triangles and base station with blue. Signal strengths are red -70 dBm, orange -75 dBm, yellow -80 dBm, green -85 – (-90) dBm and blue -95 – (-100) dBm*

When comparing the path loss estimation of the planning tool to the Okumura-Hata model for open areas, introduced in the Equation (3.16), the Okumura-Hata gives smaller values. For distances of 10 km and 13 km the path loss for the Okumura-Hata for open areas is 117 dB and 121 dB. So there is 8 dB difference in both locations. The planning tool has the clutter and altitude information so it can take shadowing into account. The planned area is quite open but there are small hills and trees which block the first Fresnel zone.

Applying the suburban area model from the Equation (3.15) introduced in the Subsection 3.3, for 10 km distance the path loss is 136 dB and for 13 km distance the path loss is 139 dB. These values are rather big with 11 dB and 10 dB difference to the planning tool. As can be noted from the Equations (3.15) and (3.16) these two models do not include the receiver antenna height. The urban model includes the receiver antenna height so using the urban model for medium to small cities and with antenna height of 10 m results in path loss of 124 dB and 128 dB. First of all the result is surprisingly close to the planning tool and secondly the path losses are smaller than with the suburban areas model. The urban model is actually the original one and the others are made by adding correction factors to the urban model [22]. The receiver antenna height is also in the maximum value and the model is normally used for a mobile CPE that is 1.5 m receiver antenna height. That is probably why suburban areas model results in greater path loss than the urban model for medium or small cities with 10 m antenna height.

5.5 Interferences to DTT Receivers

The co-channel interference to DTT receivers should not be a problem because like stated in the Subsection 5.2 there are not any co-channel contours in the direction of the transmission. In this pilot case also the adjacent channel interference to DTT receivers from the white space base station should not be a problem since the base station is located at the same mast with the DTT transmitter. The DTT signal should be so strong that it is not possible to cause so much interference, that the DTT reception would suffer. Also the white space CPE is located so close to the mast, in maximum 13 km away, that interference to DTT receivers from the CPE seems highly unlikely.

The protection ratios and the ACLR for the used WIMAX system have been measured in the radio laboratory of the Turku University of Applied Sciences. In this pilot the closest TV channel is on the second adjacent channel. In the measurements the ACLR for the CPE on second adjacent channel was 60 dB. The maximum power of the CPE is 26 dBm and antenna gain is 10.5 dBi, with 2 dB insertion and cable loss this results in EIRP of 35.5 dBm. This means that with the 60 dB ACLR the CPE radiates at -24.5 dBm to the direction of the TV receiver antenna. Because of the height of the TV transmission antenna (effective height 350 m) and the openness of the area, for 10 m receiver antenna there is line of sight to almost all receivers in the 13 km range. Hence the TV signal level in the 13 km distance is somewhere around -40 dBm. If the 20 dB C/I for TV receiver is assumed, this means that CPE's transmitted power should be attenuated to -60 dBm. This means that the CPE's transmitted power needs to be attenuated -35.5 dB before the TV receiver. This seems highly likely, since even free space loss provides -50 dB path loss in 10 m distance with antennas facing each other, so that antenna isolation is not taken into account.

5.6 DTT Interference

The white space is in some occasions also called the grey space. That is because depending on the height of the white space antenna the interference from distant co-channel DTT station can be even -70 dBm/5 MHz on supposedly free channel. [31]

There were problems with the connection in the earlier trial in Jokela and the problems were supposed to be caused by this phenomenon. The devices designed for white space use are probably more tolerant than the WiMAX devices used in this case. However, all radio equipments does have the theoretical limitation on the needed C/I ratio and so, co-channel interference has to be taken in the considerations also in the future. In the traditional case fixed connections have same coverage in uplink direction than in downlink direction. The radio path is reciprocal and the lower transmission power of the CPE is compensated with the lower sensitivity level of the base station. Now with the raised interference level in the base station, the uplink signal may drop below the interference level much earlier than the downlink signal, limiting the coverage and also uplink capacity. In the Chapters 6 and 7 this is studied and the estimated uplink coverage is also taken into account in the planning besides the downlink coverage that was calculated in this Chapter.

In this Kirkkonummi pilot case there is also two other interesting interference scenes that has to be noticed. Like mentioned earlier, Channels 52 and 53 are in use in the Espoo transmitter. When using the channel 50 there is only one guard band channel between the WiMAX and the DTT. Since the WiMAX base station uses antenna designed for the whole UHF band it will also receive the DTT signal from the channel 52 and 53. This can cause adjacent channel interference, blocking and even overloading to the base station. Blocking and front end overloading are also possible in the white space CPE side in this kind of case. The EIRP of the Espoo DTT transmitter is 77 dBm and the white space base station has EIRP of 39 dBm resulting in EIRP difference of 38 dB. This kind of difference is very likely to cause at least blocking in the receiver. Also taking account the fact that the WiMAX devices operation region is the channels 50 – 54 and there are two channels (52 and 53) used in the Espoo transmitter that are inside the operating region. In the near vicinity of the DTT transmitter the vertical pattern of the transmission antenna probably attenuates the signal in such a way, that the interference can be avoided. If however, for example two kilometers away from the mast the attenuation is no longer present and there is line of sight to the mast the signal level can be in maximum as high as -20 dBm. This kind of power is highly likely to cause at least blocking or complete saturation when the intended signal is in practice no longer amplified. The operation of the receiver can be also very unpredictable if there is intermodulations due to the receiver front end overload.

6 ESTIMATION OF THE UPLINK INTERFERENCE WITH MATLAB

It was noticed in the Jokela trial [34] that the interference in the uplink direction limited the connection more than the signal strength in the downlink direction. Although it seemed that the used WiMAX equipment had also some device specific limitations in maintaining a robust connection in this kind of interference case, the problem cannot be solved purely with hardware solutions. The possible problems with the uplink connection due to the DTT co-channel interference is also mentioned in the Report [35].

A reliable communication demands sufficient C/I ratio and higher bit rates raises the needed C/I ratio even more. The uplink limitation in the white space networks is likely to occur in the Wireless Metropolitan-Area Network (MAN) and the Wide-Area Network (WAN) solutions. In the wireless MAN and WAN white space planning the uplink limitation is an essential part of the planning process to determine the limits for the actual coverage and the uplink capacity. In the MAN and WAN solutions it is likely that the base station antenna height is over 10 m. The DTT network is designed for a 10 m receiver and so the inter system interferences are calculated for that receiver height. When using antenna height over 10 m the probability for the interferences raises. The interference scenario is also shown in the Figure 2.5. Besides the base station antenna height the interference level depends on the base station antenna directivity and the distance, height, direction and the transmission power of the DTT transmitters.

When making the first coarse estimations for the network capacity and coverage in the intended area, an estimation of the co-channel interference in the uplink is needed. To estimate the co-channel interference a Matlab function was made based on the earlier script that was used to calculate the usable channels. In this chapter the working principle of the Matlab interference estimation function is described. The purpose was to lay the ground work for the future development and see what kind of results could be achieved by using the ITU-R P.1546 model with the corrections provided in [25].

6.1 Parameters of the ITU-R P.1546 Model

The ITU-R P.1546 model is briefly introduced in the Subsection 3.3. The model is also used in the other white space signal strength and interference calculations. The advantages of this model are that usually also the TV contours are planned with this model and so the comparing of the TV and white space signal strengths is more consistent while using the same model. Other advantage is that ITU-R P.1546 can be applied for transmitting antenna heights up to 3000 m. The television transmitting antennas may have an effective antenna heights of way over 300 m and for example Okumura-Hata model cannot be used with the transmitting antenna heights of over 200 m. Also different propagation paths can be selected that is land, warm or cold sea. This is useful when adding the transmitters from the overseas to the calculations.

The basic parameters in the ITU-R P.1546 model include the transmitting antenna height h_1, defined when the terrain information is not available as:

$$h_1[m] = h_a,\ \mathrm{d} \leq 3\ \mathrm{km} \tag{6.1}$$

$$h_1[m] = h_a + \left(h_{eff} - h_a\right)(d - 3)/12,\ 3\ \mathrm{km} < \mathrm{d} < 15\ \mathrm{km} \tag{6.2}$$

where h_a is the antenna height above the ground (that is height of the mast). And h_{eff} is the effective antenna height to the direction of the receiver averaged over distances of three kilometers and 15 km from the transmitter. For the distance over 15 km the h_1 is defined as:

$$h_1[m] = h_{eff}, \tag{6.3}$$

The signal strength varies over time due to the atmospheric phenomenon's and so the ITU-R P.1546 model includes time variability in the range of 1 – 50 % which means that the signal strength is more than predicted in selected percent of time. For the interference calculations it would seem appropriate to aim to the so called worst case scenario and provide a little bit overestimation rather than an underestimation so rather to predict a little bit too strong interference strength than too low. Too optimistic predictions could lead to too optimistic plans concerning the capacity and the coverage which causes unnecessary costs when the planned and installed network does not work as intended. In these estimations time probability of one percent is used for the mentioned reasons.

The model is defined for frequencies on the scale from 30 – 3000 MHz and in this case the transmitting frequencies 470 – 790 MHz are well inside the scale. The electric field signal strength is calculated for a certain distance which is limited to 1 – 1000 km. The electric field strength is not calculated over any exact location rather than over an area. The basic model assumes 50 % location probability that means that 50 % of the area is likely to have the estimated field strength or higher. The basic model assumes a square area with a side of 200 m [25]. The location probability can be altered, but the default value is used in these calculations. With these parameters the model gives electric field strength in dBμV/m related to 1 kW ERP which can be then scaled with the actual ERP of the transmitter. The transition from field strength in dBμV/m to signal strength in dBm is defined as:

$$P(E, G_r)[dBm] = E + Gr - 20 * log(f) - 77.2, \tag{6.4}$$

where E is the electric field strength in dBμV/m, G_r is the isotropic antenna gain in dB. Since it is assumed that the wavelength of the signal is proportional to the effective antenna size, subtracting with *20*log(f)* results in changing from dBµV/m to dBµV. Subtracting 77.2 from dBµV results in dBm.

The model provides the field strength predictions for a 10 m receiver antenna. The difference in the field strength with a receiver height of 75 – 100 m is significant, especially the for several kilometers distances, which is now the case. The main point in this study is to try some corrections for the different antenna heights provided in the document [25]. Although it was not clearly stated in the document, the corrections seemed primarily meant for the antenna heights lower than 10 m so some adjustment was needed. All the used corrections are described in Subsection 6.3.

6.2 Parameters Used by the Matlab Prediction Function

The predictions are calculated on a set of test points. Test points can cover the whole Finland, but calculating the spectrum for several channels is very time consuming so in the simulations only few test points are calculated and the one point that had been measured was studied. The function goes through a one test point at a time calculating the received signal strengths from every transmitter less than 500 km away. Calculating all the transmitters throughout the country would significantly slow down the simulation. On the other hand it was assumed that the tall high power TV transmitters could interfere the white space base station antenna from several hundred kilometers away and so the 500 km seemed the appropriate limit.

The parameters for the transmitters were acquired from an Excel file from Ficora, which was loaded to the Matlab. The used transmitter file had only finish transmitters. The file was from 2010 and it was updated to match the current situation as accurately as possible. Some of the new secondary transmitters were not added at this point since they had no influence on the test points that were now studied. The databases used for the white space operations are very important to be up to date since changes do happen in the DTT transmitters and reliable and up to date information is vital. Also a receiver Excel file was made that included information about the receiver side.

The transmitter file has first of all, the coordinates for all the transmitters from which distance and direction between the test point and the transmitter is calculated. The direction is defined so that zero degrees corresponds to north, 90 degrees east 180 south and so forth. Both the transmitter and the receiver file include the effective antenna heights to all the directions in the steps of 10 degree. The transmitter file also has the ERP reduction for all the directions which concerns some of the limited transmitters. This means that in a certain direction this transmitter is allowed some certain maximum ERP to mitigate the intersystem interferences. In same way the receiver file has antenna gains for all directions depending on the horizontal antenna pattern. The field strength calculation is done with the Matlab version of the ITU-R P.1546 model. Below is shown how the actual field strength calculation function is used:

```
E = P1546FieldStr(d_km,f,time,h_eff, h_a, [],'Land') + (ERP_diff -
Erp_reduction) + 2.15;
```

where *d_km* is the distance between the transmitter and the receiver, *f* is the transmitter frequency, *time* refers to the time probability which is 1 % in this case, *h_eff* is the transmitter effective height in the direction of the receiver. The parameter *h_a* is the transmitter antenna height, *'Land'* means that the propagation is calculated on land path, *ERP_diff* is the scaling between 1 kW ERP assumed in the ITU model and the actual transmitter ERP. The parameter *ERP_diff* is calculated in the following way:

```
ERP_diff = 10*log10(ERP/1000);
```

where *ERP* means the actual transmitters ERP. The parameter *Erp_reduction* is possible reduction to the transmitter ERP as explained earlier. The constant 2.15 is the difference between scaling from ERP to EIRP introduced in the Equation (3.18).

Besides the receiver the antenna gain, also the cable loss and the corrections due to the higher receiver antenna height as in the default ITU model are added to the field strength to obtain the final estimation. The calculations of the used corrections are explained in the Subsection 6.3.

6.3 Corrections Made to Basic Model

First important aspect when using the ITU-R P.1549, was to note that the ITU recommends that the higher antenna should be considered as the transmitter and the lower as the receiver not depending on the actual operation. So the first step in the estimation algorithm is to define which of the antennas is considered to be the transmitter h_1 and which is considered to be the receiver h_2.

If the height of the receiver h_2 is different from the assumed 10 m used in the model, some corrections are needed. The starting point for the antenna height correction was correction calculation provided by the ITU in Annex 5 § 9 of the document [25]. The correction calculation includes the modified representative clutter height which takes into account the elevation angle of the arriving ray. It is defined as:

$$R'(d, h_1) = \frac{1000*d*R-15*h_1}{1000*d-15}, \tag{6.5}$$

where R is 10, 20 or 30 m depending on the area type that is 10 m for suburban area, 20 m for urban and 30 m for dense urban area. The variable d is the distance between the transmitter and the receiver, and h_1 is the antenna height of the transmitter as defined in the Subsection 6.1.

Different types of correction functions are given in [25]. The best suited for this occasion is the one concerning the receiving antenna on land in a rural or open environment. In that case the correction is given by the Equation (27b) in the document [25] for all values of h_2 with R' set to 10 m and not calculated with Equation (6.5). The Equation (27b) from [25] is as follows:

$$\text{CorrectionITU}(h_2, \mathrm{R'})[\mathrm{dB}] = K_{h_2} * \log\left(\frac{h_2}{\mathrm{R'}}\right), \tag{6.6}$$

$$\mathrm{K}_{\mathrm{h}_2}(f) = 3.2 + 6.2 * \log(f)\ , \tag{6.7}$$

where f is the frequency of the transmitter in MHz and h_2 is the height of the receiving antenna as defined in the Subsection 6.1. Although the correction function includes distance and transmitter antenna height, in practice the values depend only on the receiver height. This is somewhat insufficient in two ways. First of all when the distance is small and it is assumed that 60 % of the Fresnel zone is clear for a 10 m antenna, then the additional gain for an antenna that is higher than 10 m does not seem consistent. The maximum received power from each transmitter is calculated based on free space propagation and adding correction to nearby targets causes the estimation to reach the maximum limit in almost all occasions. So for the near targets a different correction function was used which is Equation (28a-b) in annex 5 § 9 of the document [25]. The distance where the transmitter antenna of height h_1 and the receiver antenna of height h_2 have 0.6 Fresnel zone clearance can be calculated as:

$$\mathrm{D}_{06}(\mathrm{D}_\mathrm{f}, \mathrm{D}_\mathrm{h}) = \frac{\mathrm{D}_\mathrm{f} * \mathrm{D}_\mathrm{h}}{\mathrm{D}_\mathrm{f} + \mathrm{D}_\mathrm{h}}, \tag{6.8}$$

where D_f is the frequency dependent term calculated as

$$\mathrm{D}_\mathrm{f}(f, h_1, h_2)[km] = 0.0000389\ *\ f\ *\ h_1\ *\ h_2, \tag{6.9}$$

D_h is an asymptotic term defined by horizon distances

$$\mathrm{D}_\mathrm{h}(h_1, h_2)[km] = 4.1 * \left(\sqrt{h_1} + \sqrt{h_2}\right), \tag{6.10}$$

The values for correction calculation, namely distances d_{10} and d_{h2} in km are calculated with the Equation (6.8) so that

$$\mathrm{d}_{10}(h_1, 10)[km] = \mathrm{D}_{06}(\mathrm{D}_\mathrm{f}(f, h_1, 10), \mathrm{D}_\mathrm{h}(h_1, 10)), \tag{6.11}$$

$$\mathrm{d}_{\mathrm{h}2}(h_1, h_2)[km] = \mathrm{D}_{06}\big(\mathrm{D}_\mathrm{f}(f, h_1, h_2), \mathrm{D}_\mathrm{h}(h_1, h_2)\big), \tag{6.12}$$

Now the calculated values of distances d_{10} and $\mathrm{d}_{\mathrm{h}2}$ define the used correction as shown in the Equations (6.13 – 6.15)

$$\text{CorrectionITU}[\mathrm{dB}] = 0,\ d \leq d_{h2} \tag{6.13}$$

$$\text{CorrectionITU}(\mathrm{C}_{10}, \mathrm{d}_{\mathrm{h}2}, \mathrm{d}_{10}, d)[\mathrm{dB}] = \mathrm{C}_{10} * \frac{\log\left(\frac{\mathrm{d}}{d_{h2}}\right)}{\log\left(\frac{\mathrm{d}_{10}}{\mathrm{d}_{\mathrm{h}2}}\right)}, d_{h2} < d \leq d_{h10} \tag{6.14}$$

$$\mathrm{C}_{10}(\mathrm{K}_{\mathrm{h}2}, h_2) = \mathrm{K}_{\mathrm{h}2} * \log\left(\frac{h_2}{R'}\right), R' =\ 10 \tag{6.15}$$

where d is the actual distance between the transmitter and the receiver, d_{10} is the distance where 0.6 of the Fresnel zone is clear for an 10 m antenna and d_{h2} is similarly the distance where 0.6 Fresnel is clear for an antenna height of h_2. According to the Equation (6.13) when the distance d is smaller than the distance where there is 0.6 Fresnel clearance for the antenna heights of h_2 and h_1, then no correction is needed. When the distance d is between the 0.6 clearance zone for the antenna heights of h_2 and 10 m antenna, there is a transition zone. In the transition zone the correction values increase logarithmically toward the maximum correction C_{10} so that it is between $C_{10} * e$ and $C_{10} * (1 - e)$, e being the epsilon.

The correction function for the shorter distances in its original form as introduced in [25] and also shown in Equations (6.13, 6.14 and 6.15), is not applicable to the situation where $h_2 > 10$, which is usually the situation in this case. When $h_2 > 10$ and hence $d_{h2} > d_{10}$ it is assumed in the estimation function that the correction could be calculated as:

$$\text{CorrectionITU2[dB]} = 0,\ d \leq d_{10} \tag{6.16}$$

$$\text{CorrectionITU2}(d, d_{10}, d_{h2})[dB] = C_{10} * \frac{\log\left(\frac{d}{d_{10}}\right)}{\log\left(\frac{d_{h2}}{d_{10}}\right)}, d_{10} < d < d_{h2} \tag{6.17}$$

The transition to the maximum correction in the Equation (6.17) brings a problem in this case. It might be due to the fact that this transition is planned for cases were receiver is lower than the default 10 m, not higher. One significant difference between this case and the original ITU definition is that when h_2 is between the values $1 \leq h_2 < 10$ m it leads to much shorter transition zones when compared to the situation when h_2 is for example between the values $10 < h_2 \leq 120$ m. The problem with the transition region is illustrated in the Figure 6.1.

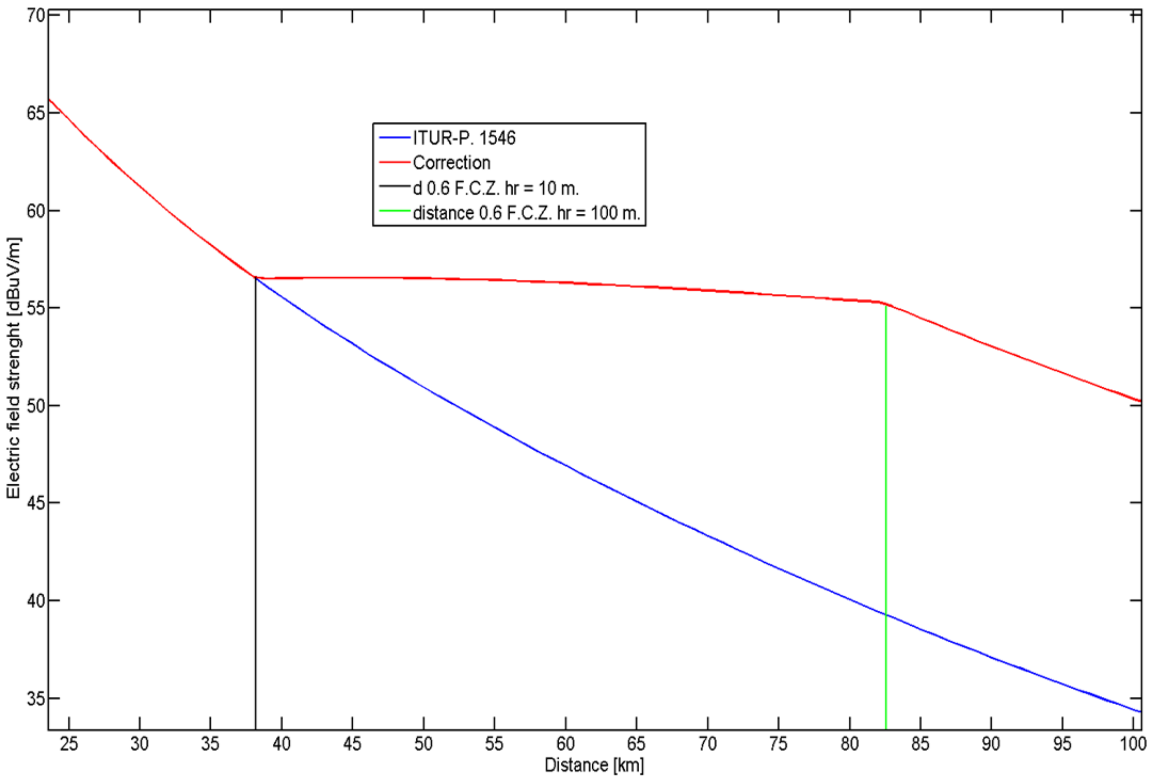

Figure 6.1 *Example of the behavior of the correction function. Parameters h_1 = 300 m, f = 600 MHz, time = 1%, h_2 = 10 m (blue line), corrected h_2 = 100 m (red line)*

As we can see from the Figure 6.1, in the transition zone the correction function is almost constant. This is not natural behavior for the electric field strength in these distances and would make the estimation function non consistent in the transition zone. The solution used in this case is to limit the transition to obey the behavior of the free space loss scaled to start from the distance d_{10} with the electric field strength calculated with the ITU-R P.1546 model. From the distance d_{10} to the distance d_{h2} the transition is calculated as:

$$\text{CorrectionFSL}(E_{fs}, E) = E_{fs} - \left(E_{fs} - E\right),\ d_{10} < d < d_{h2} \tag{6.18}$$

$$\text{Correction} = \min(\text{CorrectionITU2}, \text{CorrectionFSL}), d_{10} < d < d_{h2} \tag{6.19}$$

where CorrectionFSL is the correction with the scaled free space loss, E_{fs} is the electric field strength calculated with the free space loss and E is the electric field strength calculated with the ITU-R P.1546 model. In the next figure there are illustrated E, E_{fs} and the original correction that was calculated based on the ITU.

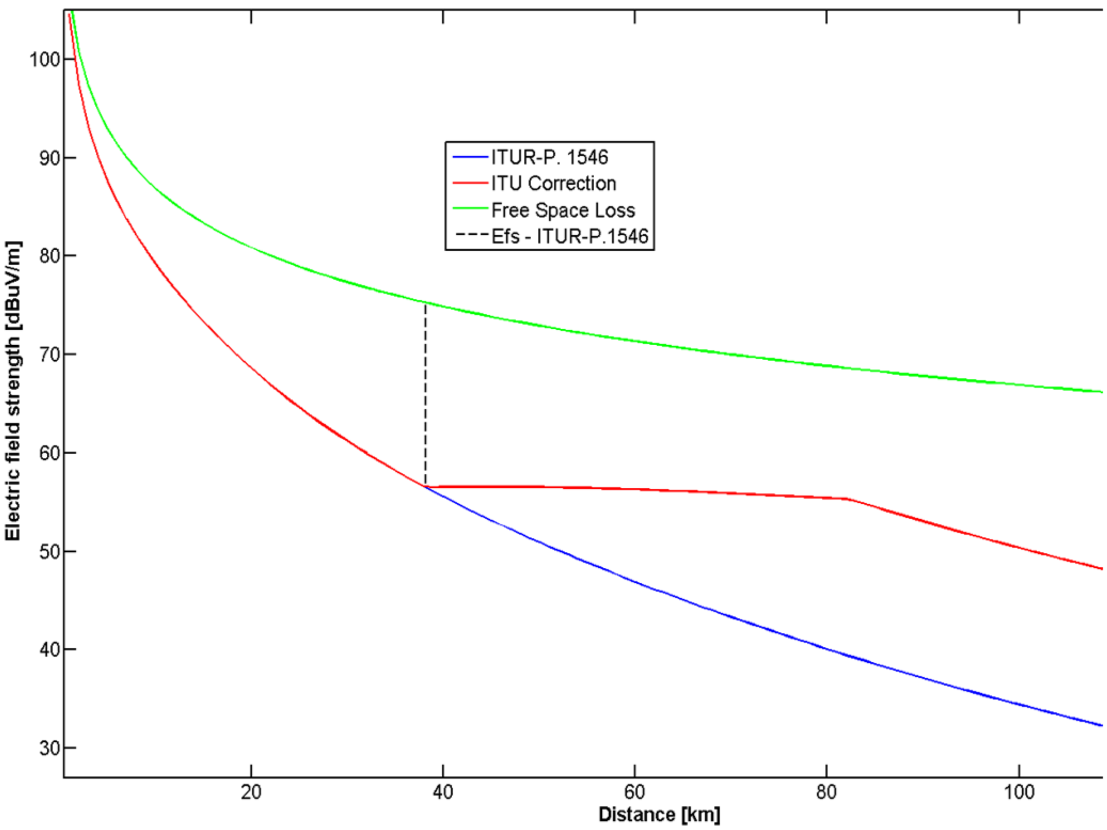

Figure 6.2 *Field strengths of the ITU-R P.1546, the correction function and the free space loss*

In the Figure 6.2 is depicted how the three graphs behave. The difference *Efs – (Efs – E)* is depicted with the dashed line. In the Figure 6.3 the free space loss is scaled to start from the electric field value calculated with the ITU-R P.1546 model in the distance d_{10}.

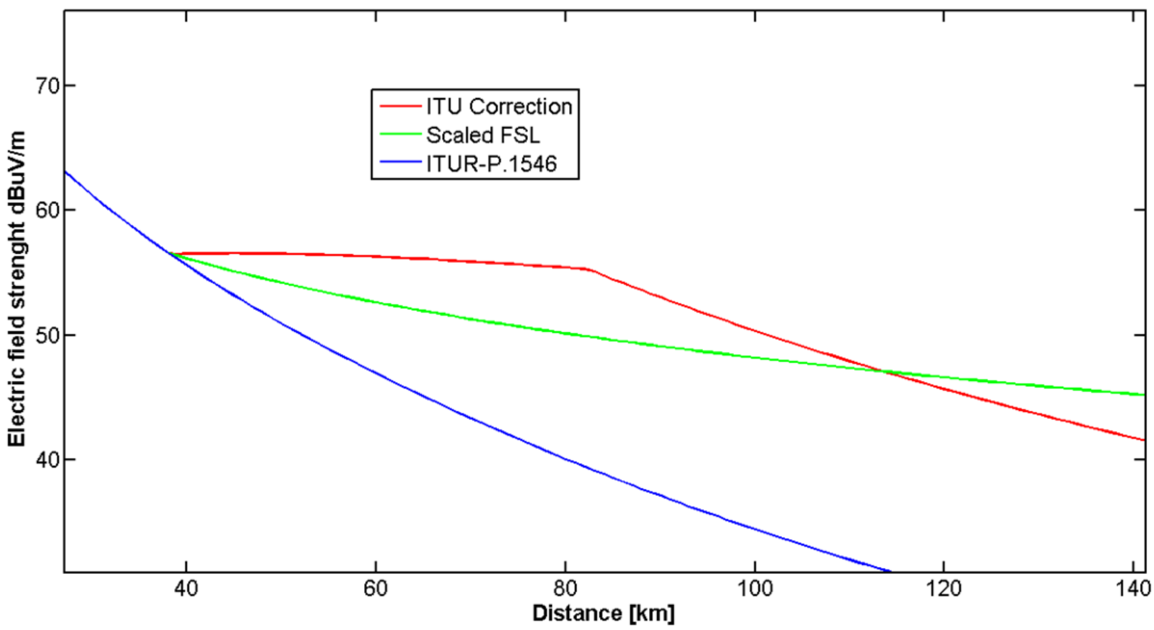

Figure 6.3 *Illustration of the behavior of the original ITU model, the correction and the scaled free space loss in the transition zone*

From the Figure 6.4 we can see that the transition is now more smoother, but the correction cannot be in the maximum in the distance d_{h2} since it would cause a sharp edge to the correction in that point. After the distance d_{h2} the CorrectionFSL might still be needed if the CorrectionITU2 is greater in the distance d_{h2}. It is not convenient to calculate both corrections in the all distances after d_{10}, so it seemed sufficient solution in this point to limit the examination to 150 km. A more exact definition could be in place in future, but based on the experiences on the functioning of the model the limit seems appropriate for time being. The final form of the correction calculation is as:

$$Correction[dB] = \begin{cases} 0,\ 0 < d < \mathrm{d}_{10} \\ \min(\mathrm{CorrectionITU2}, \mathrm{CorrectionFSL})\,, \mathrm{d}_{10} < d < 150 \\ \mathrm{CorrectionITU}, d > 150 \end{cases} \qquad (6.20)$$

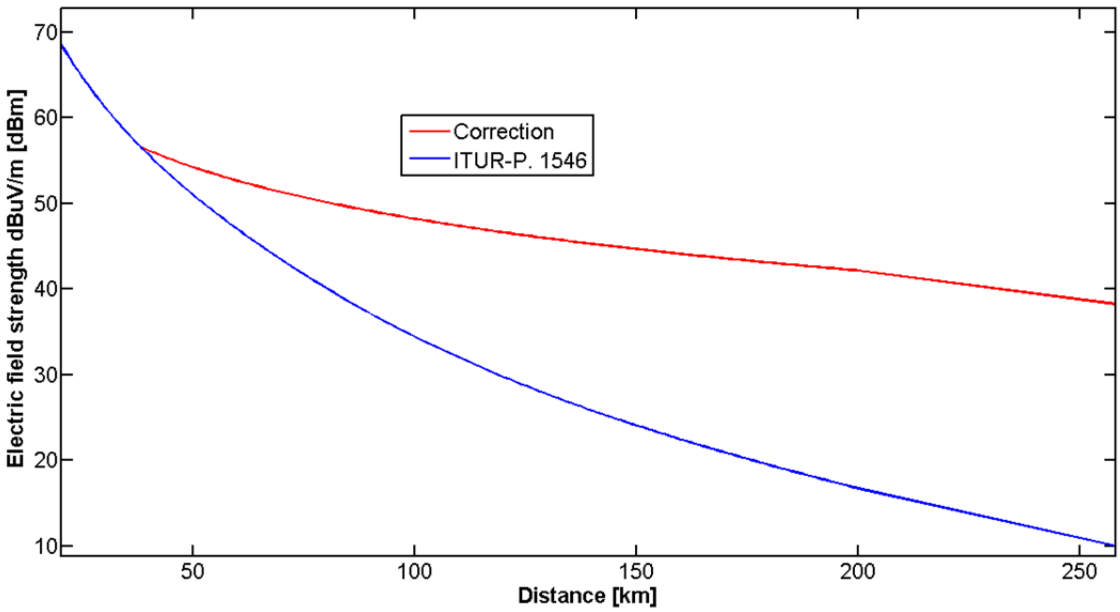

Figure 6.4 *Behavior of the used correction in example case where h1 = 300 f = 600 time = 1%, the 10 m receiver field strength values in blue and 100 m in red*

In the Figure 6.4 is an example graph of the correction in one case. The adjustments introduced in this chapter applied to the correction formulas provided by the ITU, has resulted to seemingly consistent behavior of the correction. In the Chapter 7 the results from the estimation function introduced in this Chapter is compared to the actual interference power measurements from three different locations.

7 MEASUREMENTS AND RESULTS

This Chapter describes first of all the measurements that were completed to evaluate the accuracy of the interference estimation function described in the Chapter 6. This was done by making spectrum measurements from the white space antennas that were already installed and hence available. The antennas were located in Jokela, Pasila and Espoo which was installed for the network planned in this thesis. The spectrum measurement locations are shown on a map in the Appendix, with the closest DTT transmitters.

At first the purpose was to measure the channels that could be used by the white space devices. In practice the problem was that the dynamic range of the used spectrum analyzer was not sufficient for measuring the lowest signal levels reliably. For reliable measurements channel filters would be needed, but that was not possible within the planned timeline. For comparison purposes reliable interference signal powers were used, meaning power levels inside the dynamic range of the spectral analyzer, but not necessarily on channels that could be used for white space operation. The low interference channels are the most important for the white space operation. For the future development one essential point would be to enhance the estimators operation with reliable signal levels from the low interference channels.

The received power in certain location from the DTT transmitters varies greatly temporally. In measurements recorded in Jokela between 20.5.-98 – 29.6.-98 there has been even 20 dB difference between the minimum and maximum field strength values of the DVB-T signal [36]. The large variations in the DVB-T field strength are partly explained by the high power of the transmitters. Weather conditions affect the propagation conditions temporally [24]. Small relative variations in the signal strength result in large absolute variations because of the high power. Other explanation is that when using the high transmitter antennas in the UHF band the radio wave is vulnerable to the tropospheric ducting. In normal conditions the radio wave bends slightly towards the Earth but vanishes to the horizon little after the line of sight. In the tropospheric ducting the radio wave bends sharply towards the Earth from the troposhere, after which it bounces back and bends again. This bouncing between the troposphere and the Earth causes the wave to propagate much further than in normal conditions [24]. The tropospheric ducting causes high field strength values compared to normal conditions and thus increasing the difference between the maximum and the minimum values.

Only one measurement from the studied locations is not nearly the whole truth but was considered as sufficient reference for the estimation function. The purpose of the function is to give coarse estimations in the early stages of the network planning to see if the implementation of the intended network seems possible. In addition to causing challenges in the estimation, the great variations in the DTT field strengths affects the operation of the white space network and it is vital to remember to avoid costly surprises.

Besides comparing the measured and the estimated signal strengths, the estimation function is used in two ways. In the Subsection 7.1 the number of usable channels in Espoo is estimated using the estimation function and using a certain maximum interference threshold level. The other example ties together the different aspects introduced in this thesis. Based on the uplink interference level, the uplink coverage is calculated in two occasions. One is the channel 50 used in this case and the other is the lowest co-channel interference channel based on the estimation function. The uplink and the downlink estimations are combined for determining the actual capabilities of the planned network. In the last part are described the connection measurements from the Espoo network and the measurement results are compared to the estimated ones.

7.1 Base Station Antenna Measurements in Espoo

The uplink interference spectrum was measured from the antennas described in the planning Subsection 5.4. The Table 7.1 shows the measured signal strengths of the DTT transmitters over 7.62 MHz wide channels.

Table 7.1 *The measured DTT transmission signal strengths from the base station antenna*

Channel	28	30	32	33	35	37	39	40	42	43	50	51	52	53	55	56	57
Measured signal strength [dBm]	-43	-48	-34	-71	-44	-51	-74	-81	-55	-74	-78	-75	-38	-38	-75	-79	-73

From the Figure 7.1 we can see the DTT transmitters' signal strengths that were measured from the Espoo antenna together with the estimated signal strength calculated with the estimation function and also the estimate based on the free space loss model. The free space loss estimate includes the effects of antenna gains and the cable and the insertion losses. The free space loss propagation model does not include any information about the transmitter or the receiver heights, only distance and frequency.

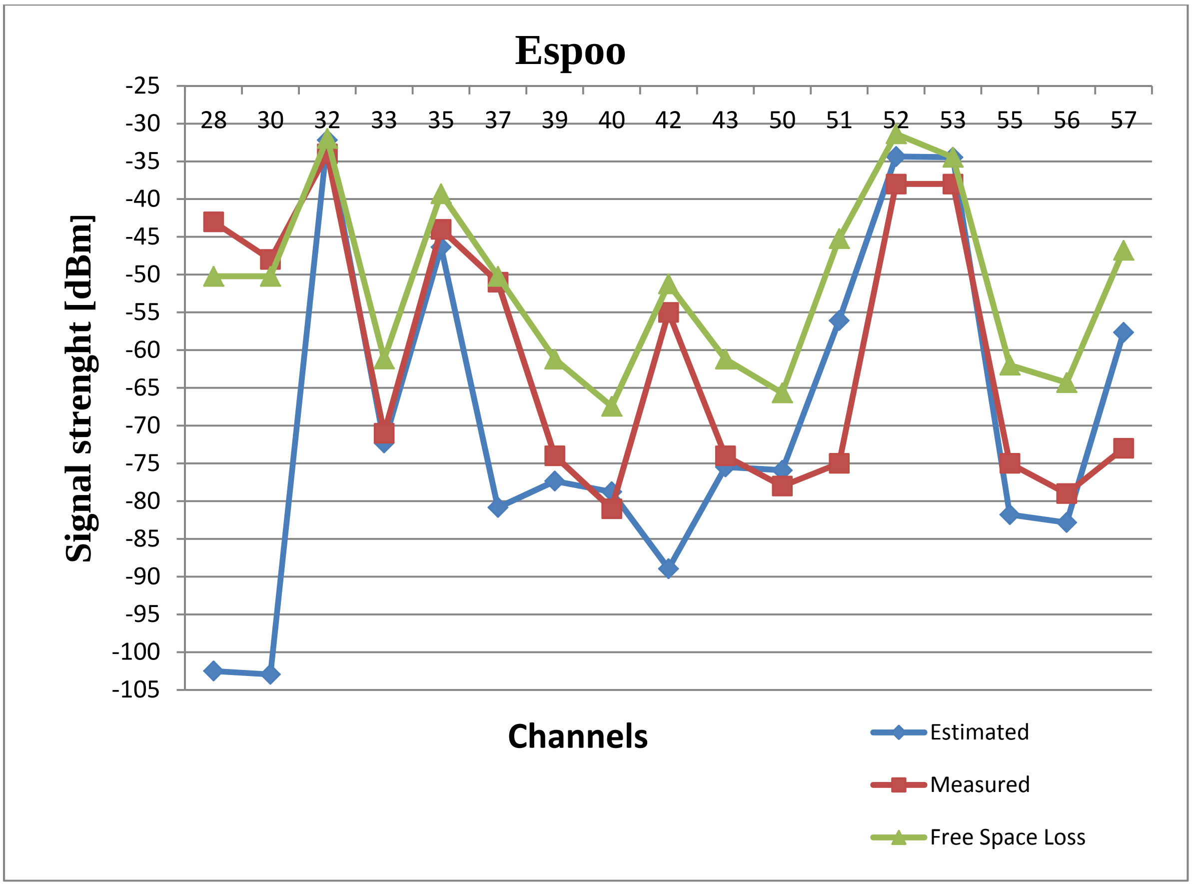

Figure 7.1 *Measured and calculated signal strengths from the Espoo antenna.*

First of all there are interesting results in the channels 28, 30, 37 and 42. In these channels the measured signal strength is much higher than even the calculation assuming free space loss. This should not be even physically possible so some further investigation was needed. Like mentioned in the Chapter 6 the file containing the transmitters does not have the information on foreign transmitters at the moment. The reason for these unexpectedly high signal levels turned out to be Estonia Teletorn transmitter which operates in these channels. These channels seemed good for the white space use because there are not any Finnish transmitters in the near vicinity, but the reason for that came clear after discovering the Estonia transmitter.

To get the spectrum figure right the Estonia transmitter power levels were added manually at this point, but it is clear that one vital future development is adding the foreign transmitters' information to the transmitter file. The Figure 7.2 depicts the profile figure between the Estonia transmitter and the Espoo antennas.

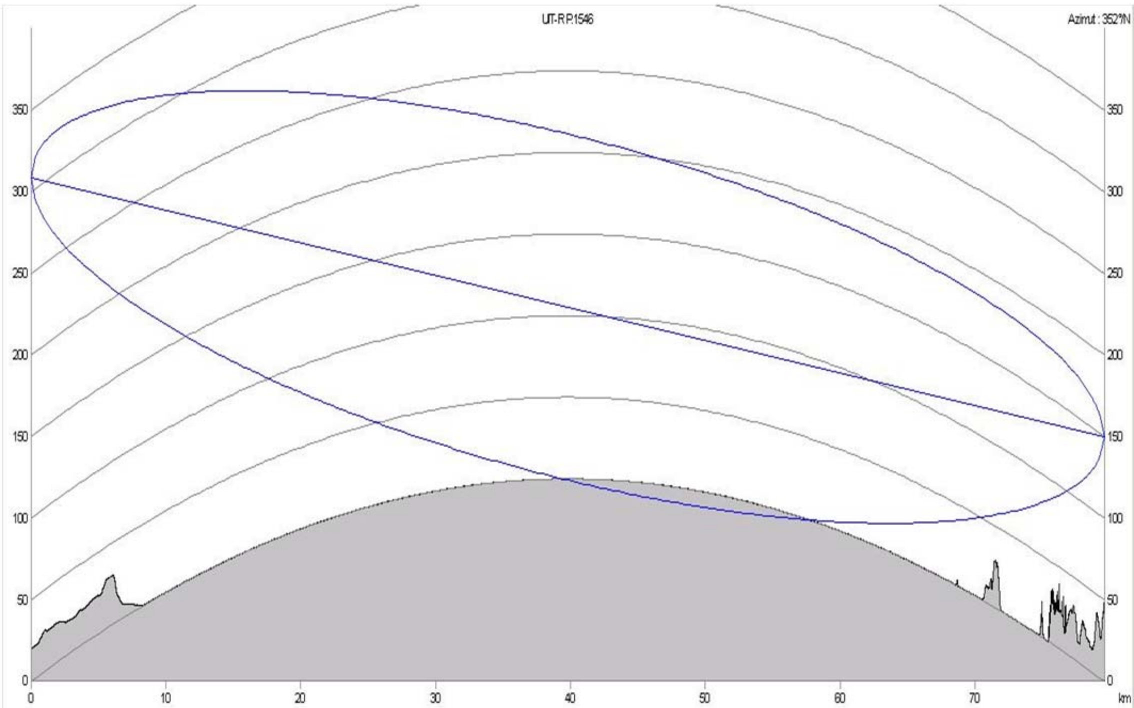

Figure 7.2 *Profile between the Estonia Teletorn and the Espoo antenna.*

The teletorn has an effective antenna height of 313 m towards Espoo and Espoo antenna has an effective antenna height of 147 m towards Estonia and as it can be seen from the Figure 7.2 that there is practically a first Fresnel zone clearance between the antennas. For the signal strength calculation the free space propagation is used, adding the antenna gain and the cable loss.

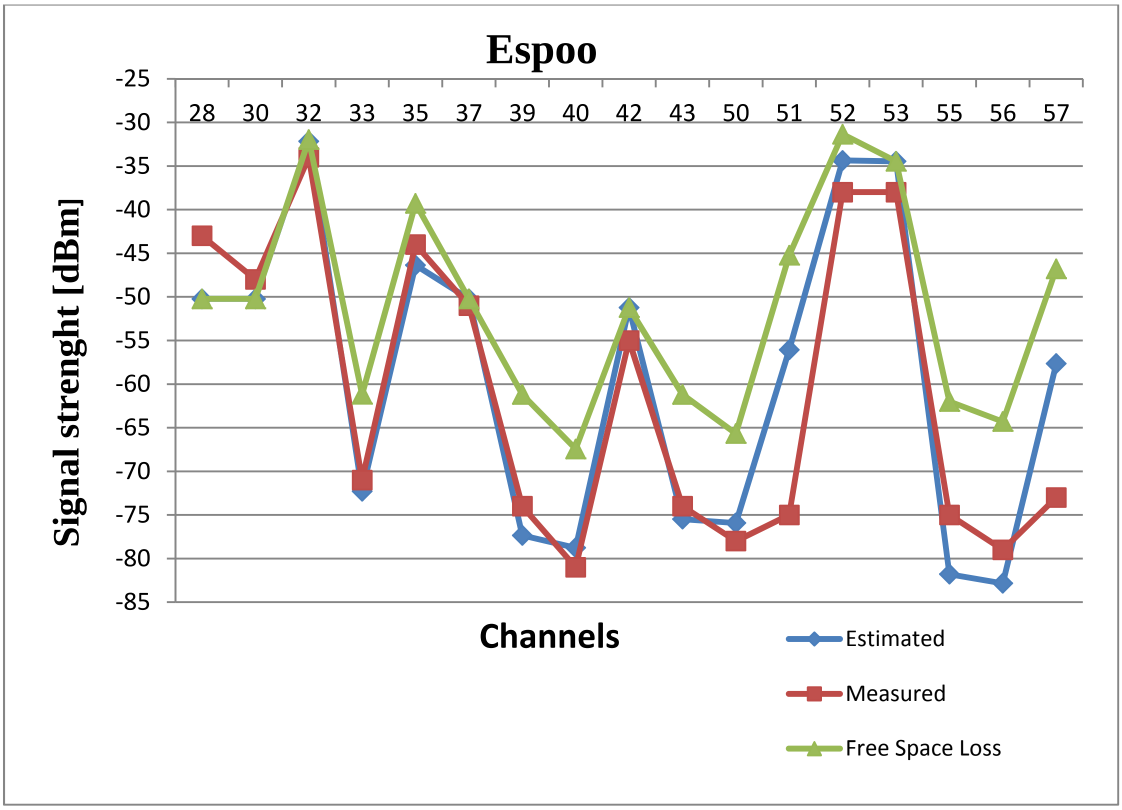

Figure 7.3 *The measured and the estimated signal strengths from Espoo, added with the Estonia transmitter.*

The Figure 7.3 shows that after correcting the missing Estonia transmitter to the Espoo signal strength graph the only clear cases of failure of the estimation function is on the channels 51 and 57. On these channels is the Turku transmitter and it seems that there is no clear reason for this. The profile picture between the Turku transmitter and the Espoo white space antenna is in the Figure 7.4.

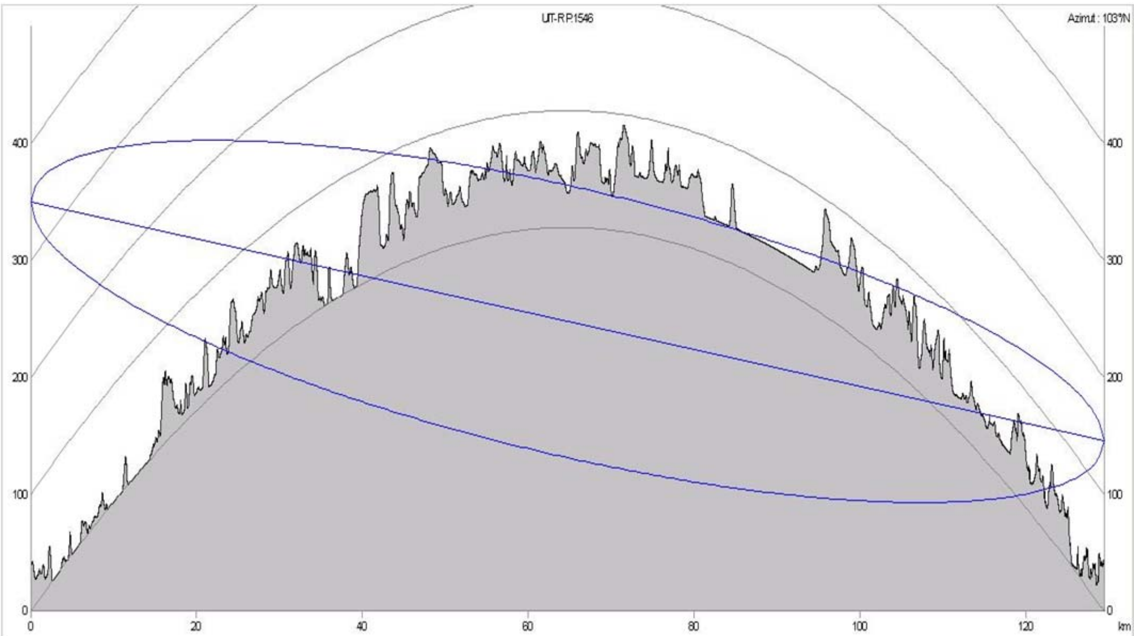

Figure 7.4 *Profile picture between the Turku transmitter and the Espoo White Space antenna*

As can be seen from the Figure 7.4 the curvature of the Earth is shadowing the first Fresnel zone even without taking into account the geological profile, so the ITU-R P.1546 model should be able to estimate the signal strength more accurately. In this case it seems that the used correction fails.

The estimated interference level could be now used for determining the usable channels. The estimation is done for this purpose over the whole 470-790 MHz band and not only on the measured channels. A Threshold is defined in such a way that every channel that has the same or lower interference level than the threshold is selected. Taking for example the threshold of -75 dBm and not using the adjacent channels with the DTT transmission results in a list of usable channels presented in the Table 7.2.

Table 7.2 *Interference level on the so called good channels in Espoo.*

Channel	23	25	26	38	39	40	41	50	55	56	59
Interference Strength [dBm]	-76,5	-75,5	-79,5	-84,3	-77,3	-78,8	-83,8	-75,9	-81,8	-82,8	-85,7

Comparing the usable channels to the ones calculated in the Subsection 5.2 the amount is clearly more. With the guard distances and the guard band used in the Subsection 5.2 there were three usable channels; 30, 37 and 38. Due to the Estonia transmitter 30 and 37 are not usable so 38 is the only channel fulfilling the both requirements.

7.2 Base Station Antenna Measurements in Jokela

From the previous white space trial there were antennas installed to Jokela measurement station. Antenna height is 75 m and the cable and the insertion loss is about 6 dB. Two UHF-band H-polarized antenna panels are used with power splitter and antenna gain of 11.5 dBi. The antenna pattern is shown in the Figure 7.5.

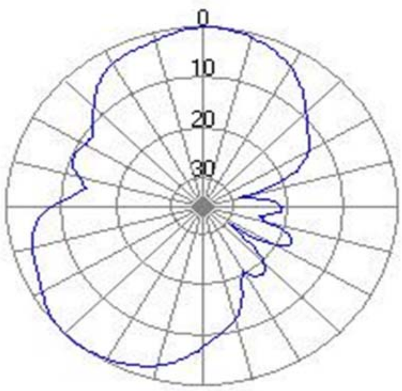

Figure 7.5 *Antenna pattern of the antennas in Jokela*

The Table 7.3 presents the measured DTT transmitters' signal strengths from the Jokela antennas. The Figure 7.6 presents the measured, estimated and the free space loss calculated values from the Jokela antennas.

Table 7.3 *The measured DTT transmitters' signal strengths from Jokela antenna*

Channel	23	24	25	27	28	29	38	39	42	43	57	58	59	60
Measured Signal Strength [dBm]	-53	-31	-77	-60	-53	-54	-79	-63	-79	-62	-40	-66	-75	-75

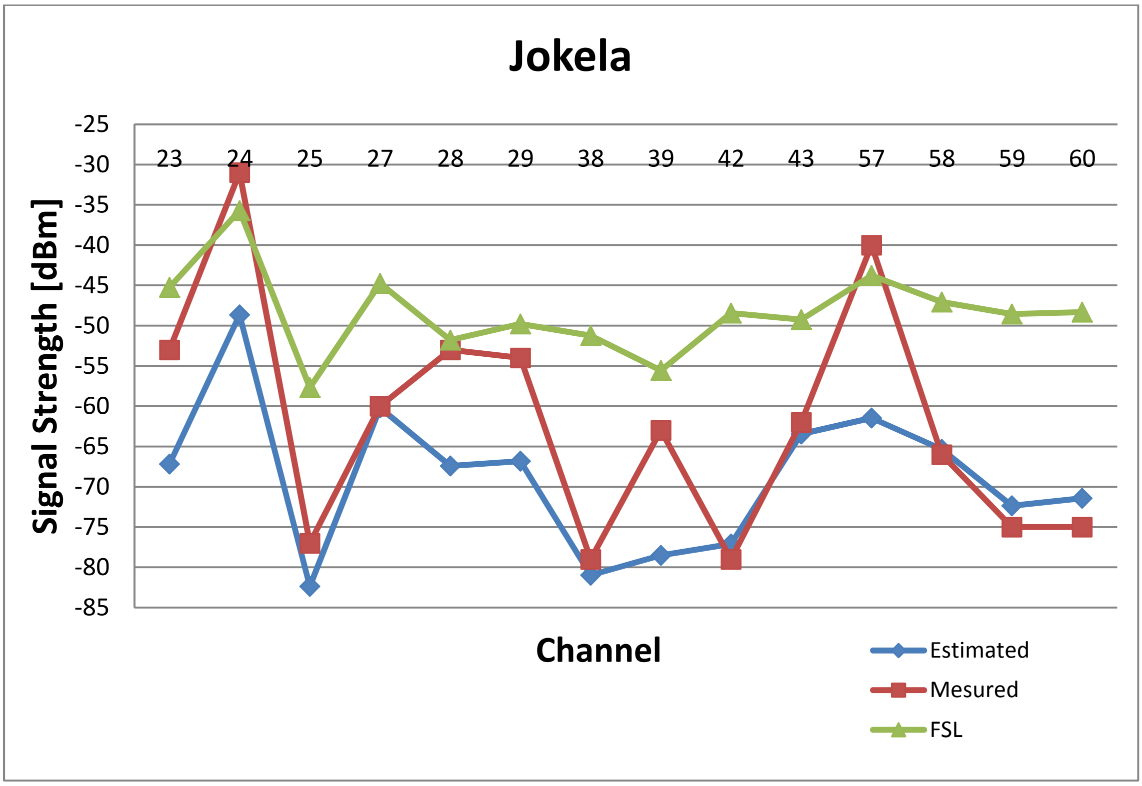

Figure 7.6 *The estimated signal strengths with the ITU model and the free space loss and the measured.*

Jokela proved to be hard to estimate because of the location and the geological properties of the area. The points where the model fails are mostly cases where the estimated value is significantly lower than the measured. In the Figure 7.7 and Figure 7.8 are depicted situation in the channels 24 and 57. In the channel 24 the most significant signal power comes from the Espoo transmitter and in the channel 57 the signal strength is due to the Lahti transmitter. The channels 28 and 29 are used in the Hyvinkää transmitter.

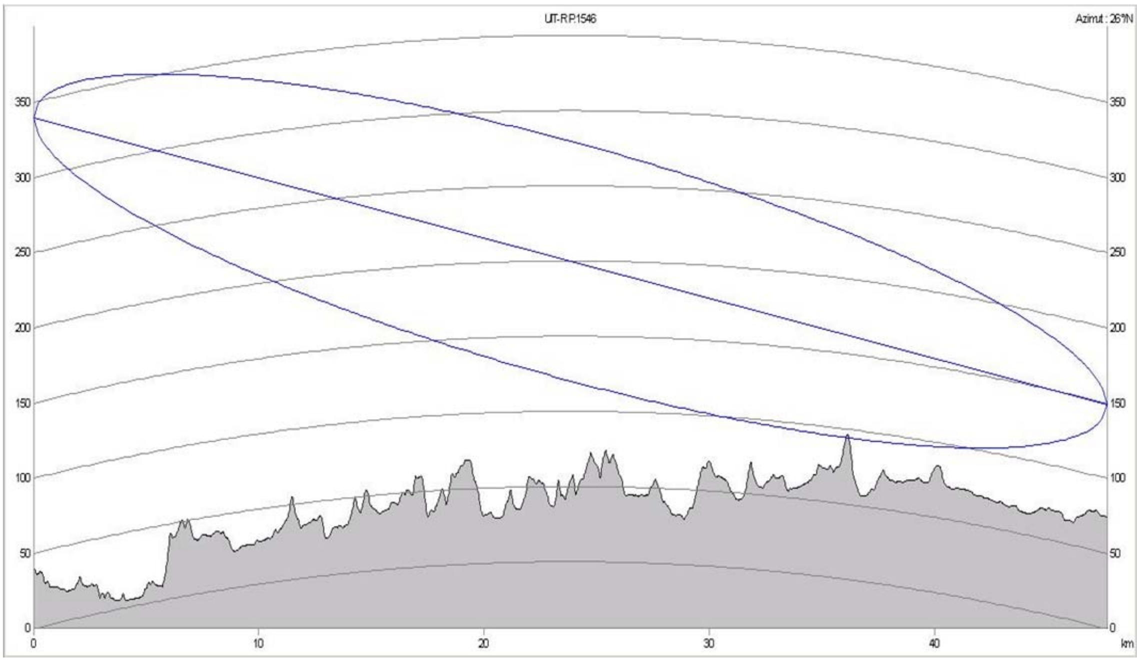

Figure 7.7 *Profile picture between the Espoo transmitter and the Jokela antenna.*

From the Figure 7.8 we can see the line of sight that the Espoo transmitter 48 km away has to the 100 m high Jokela antenna. On the other hand this channel could not be used anyhow because the co-channel contour is too close.

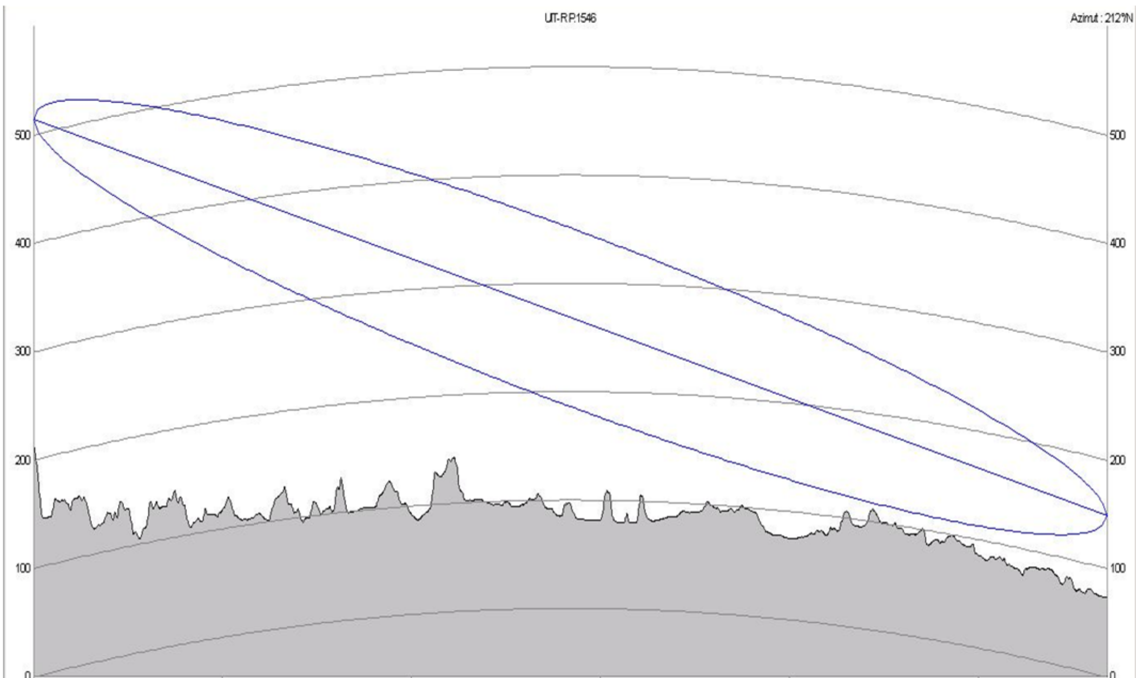

Figure 7.8 *Profile picture between the Lahti transmitter and the Jokela antenna*

The Lahti transmitter has also a line of sight to the Jokela antenna despite of the 57 km distance, due to the especially high effective antenna height of the transmitter. In this case also Jokela is almost inside the Lahti transmitters contour so using the channel would not be possible anyway. In the similar manner the Hyvinkää transmitter is only 10 km away and the channel could not be used.

The most important point in these cases, despite the errors between estimation and measurement, would be that the estimation method would show that the channel is not usable. This would be beneficial when estimating the possibly usable channels solely based on the interference level on the channel. The estimated interference levels on the channels 24 and 57 that is, -49 and -61 dBm, clearly states that there is strong DTT signal strength in the channel although it is actually major underestimate.

In the channels 28 and 29 the estimated level (-67 dBm) is still quite sufficient to show that the channel is used somewhere too near and the white space operation is not possible. In the channel 39 there is possibility to assume the channel as usable with the interference level of -79 dBm althought the measured value is -63 dBm. The situation in the channel 39 is very much the same as with the Espoo and Lahti transmitters.

In the channel 39 the main signal power comes from the Pernaja main transmitter 51 km away and it has a line of sight and few obstructions inside the first Fresnel zone. It seems that the estimation gives consistently too low signal levels for main transmitters located approximately 50 km away. This could suggest that the correction in the transition zone is too little. As stated before, if the channels are cut down before the interference estimation, all of these problematic channels would be left out because of the too near co-channel contour. But in case the estimator is used as the main information to determine the possible amount of the free channels in the area, then situations like the channel 39 in this case, would provide false results.

7.3 Measurements in Pasila

The Pasila antenna was also installed during the previous trials to the Pasila TV station. The antenna is located in the Pasila TV mast and the antenna height is 100 m. The antenna is a typical UHF band antenna with the antenna gain of 12 dBi.

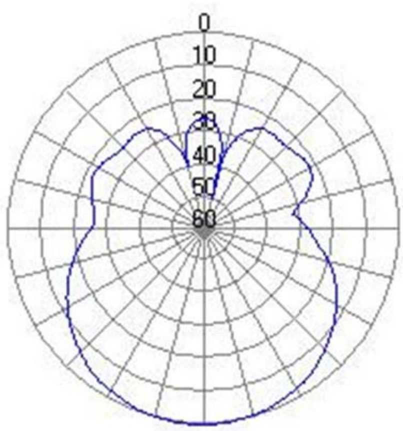

Figure 7.9 *The antenna pattern and the direction of the Pasila antenna.*

The Table 7.4 presents the measured DTT signal powers from the Pasila antenna. The Figure 7.10 shows the graph of the estimated, the measured and the free space loss calculated signal strength values from Pasila.

Table 7.4 *The measured signal strengths from the Pasila antenna.*

Channel	22	23	28	29	30	31	32	35	37	38	39	40	49	50	53	54
Measured Signal Strenght [dBm]	-80	-76	-75	-87	-87	-86	-53	-22	-79	-84	-78	-79	-85	-76	-62	-87

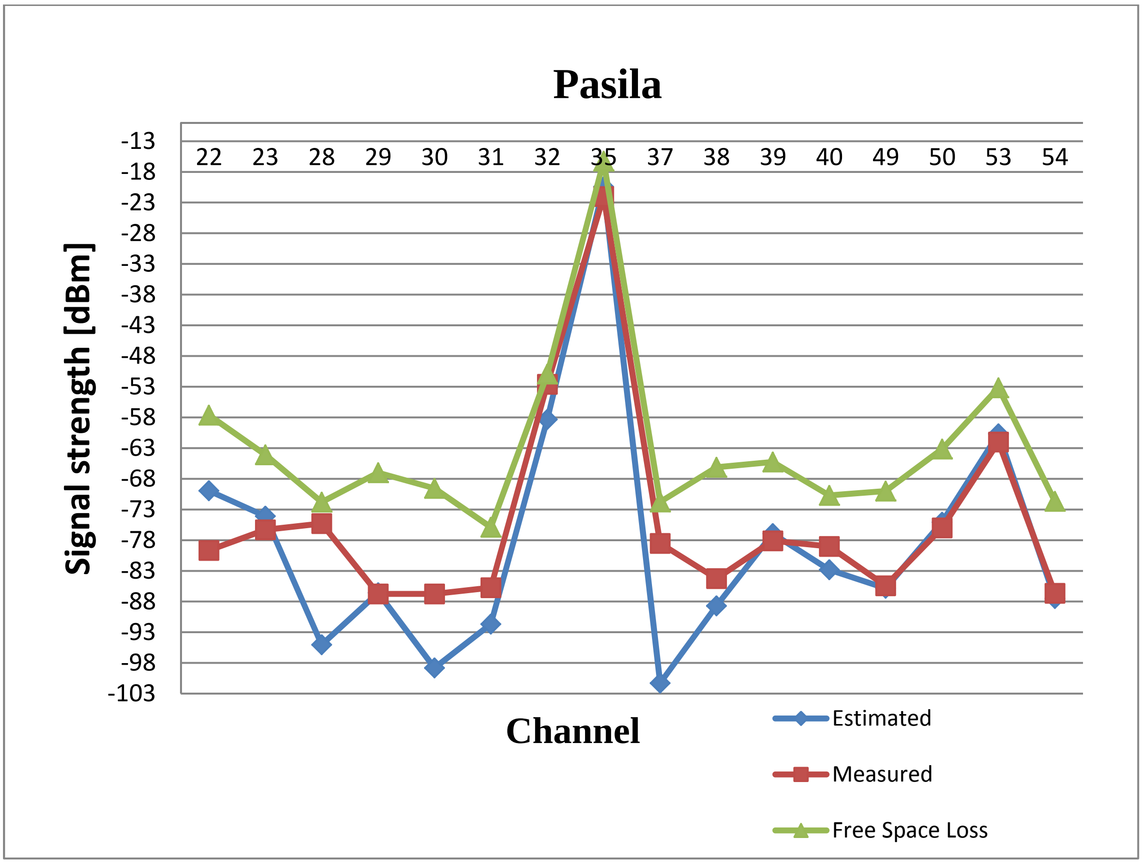

Figure 7.10 *The Estimated signal strengths with the ITU model and the free space loss and the measured.*

The points where the estimation fails are again on the channels that are used in Estonia. However, adding the Estonia transmitter signal strength in this case makes the estimation go way over the measured signal strength. There does not seem to be a clear explanation why the measured values from Pasila in the channels used in Estonia differ so much from the ones measured in Espoo.

At least what is consistent is that all the Estonia channels have much lower power levels than could be expected. It could be for example that the incoming signal from the Estonia comes in such an angle that it hits a low point in the vertical antenna pattern of the Pasila antenna. Otherwise the estimation seems quite reliable in the Pasila case.

7.4 Calculation of the Uplink and the Downlink Coverage and Capacity in the Kirkkonummi Case

The white space network planning has so far covered the determination of the usable channels by avoiding interference to the TV receivers. The interference avoidance includes proper safety distances to the co-channel and the adjacent channel TV contours and also sufficient frequency guard bands.

After determining the usable channels based on protecting the TV service, the DTT transmitters' interference to the white space base station is estimated. With the estimation and known C/I ratios of the used system, the coverage and the capacity can be estimated with a suitable propagation model.

In the following, some examples are shown of the last phase. The Figure 7.11 introduces the uplink coverage and capacity in the Kirkkonummi pilot case with the equipment used in the pilot. Then the coverage and the capacity of the uplink in the Kirkkonummi case are analyzed when all the channels could be exploited and the best one is chosen. The parameters of the actual white space devices are not taken into consideration at this point since there is no reliable information on the actual C/I ratios.

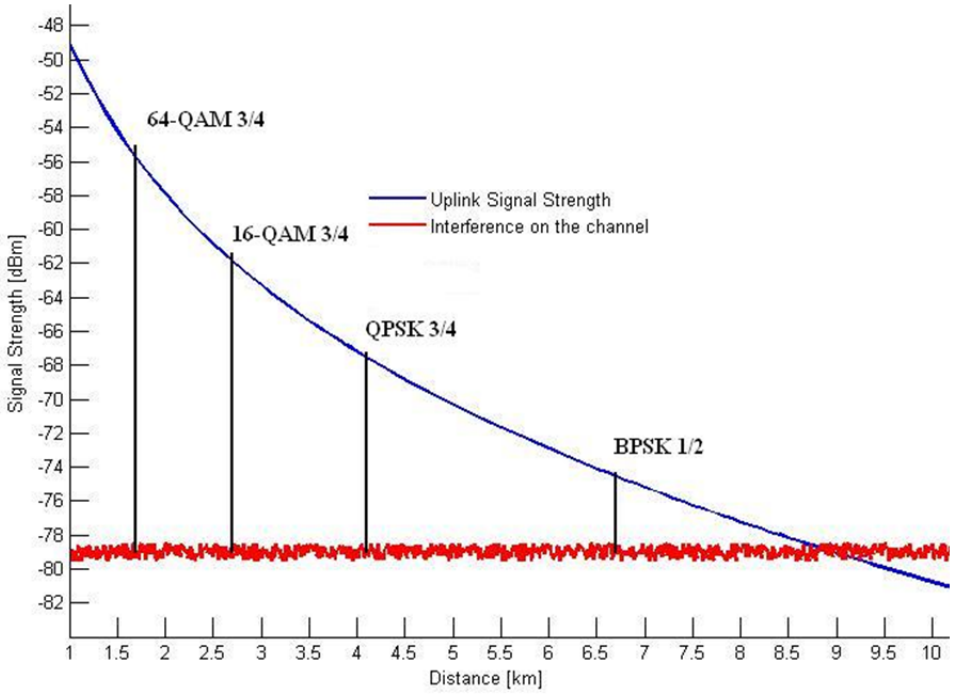

Figure 7.11 *The coverage on the different capacity thresholds in the uplink direction for the WiMAX equipment in the Espoo antenna using channel 50.The used parameters for the ITU-R P.1546 model: EIRP = 35 dBm, time = 50%, f = 706 MHz*

In Chapter 5 it was estimated that in the downlink direction a site located 13 km away from the base station could be covered. The downlink signal strength was estimated to be -81.8 dBm and the receiver sensitivity was proven to be -83 dBm in the laboratory test with 16-QAM ½ modulation. The connection worked with a minimum -88 dBm received signal strength. The Figure 7.11 shows that with the measured interference level on the channel and with the same propagation model as used in the downlink estimation, the uplink will work only about 6.7 km away from the base station.

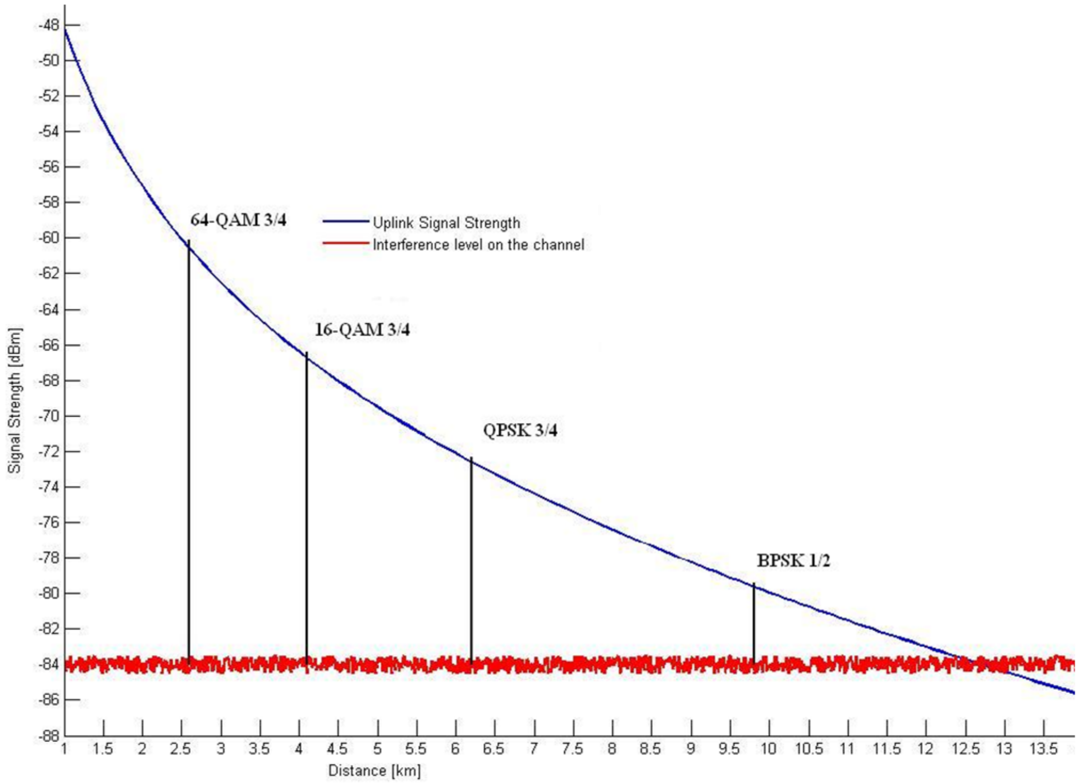

Figure 7.12 *The coverage and the capacity on the channel 41 with the same parameters as in the Figure 7.11, but with f = 643 MHZ.*

The Figure 7.12 illustrates the uplink coverage and capacity assuming that the devices could use any channel from the region 21-60. The lower interference level results in coverage extension to roughly 10 km and the uplink and the downlink are much more in balance than in the channel 50. In addition to the limited frequency operation region, one important feature of the used devices was compliance with the IEEE 802.16-2004 standard and hence lacking of the MIMO support. MIMO is supported in the both white space devices introduced in the Chapter 4 to enhance the tolerance toward the co-channel interference.

7.5 Connection Measurements in Espoo

One day field tests were accomplished in Espoo and Kirkkonummi on purpose to see the overall performance of the network and to get some results on the coverage and the capacity. Later on there will be more comprehensive field tests but already here enough results were acquired to supplement the theoretical calculations introduced in this thesis. The measurements were done with the Digita's measurement van. The van has a telescopic mast that can be lifted to a 10 m height. In the measurements the van was parked to a suitable location and the antenna was lifted to 10 meters since the network planning was done with this receiver height. In every point the connection was tested and the parameters were acquired from the devices. On the other hand it could be that the parameters provided by the devices are not absolutely accurate, but then again it is probably how the devices' see the channel properties and that is what matters most.

The base station was installed in a device cabin in the root of the Espoo mast. It was connected over the Internet with a virtual local area network to a computer in the laboratory of the Digita's headquarters in Pasila. The computer had the database agent software running that connects the Fairspectrum database and provides the intended channel and the coordinates of the device. The information about the channel and the coordinates are written manually to a text file. The database replies whether the intended channel is available in the given coordinates. If the channel can be used then the agent turns on the radio of the WSD. Through the laboratory there was also connection to the Internet and the approximate bit rates of the connection were acquired using the Sonera's speed test on the Internet. The measured points are depicted in the Figure 7.13. The points where the connection worked are marked in green and point where the connection could not be established is marked in red.

Figure 7.13 *The measured points in Espoo.*

The measurements started beneath the mast to make sure that the connection worked. At first the connection did not work since the WiMAX base station limited the CPE's transmission power. After changing the setup so that the CPE could use full transmission power, the connection was established. From the Table 7.5 we can see the measured results from different measurements points.

Table 7.5 *The results from the Espoo measurements*

	DL speed [Mbit/s]	UL speed [Mbit/s]	DL RSSI [dBm]	UL RSSI [dBm]	DL Eff. SNR [dB]	UL Eff. SNR [dB]	DL modulation	UL modulation	lat. [ms]	Distance [km]
1	12,8	2,58	-58	-69	30,2	11,83	64-QAM 3/4	QPSK	49	0,1
2	1,52	7,67	-48	-60	3	22,04	BPSK 1/2	16-QAM 3/4	25	1,8
3	6,19	7,86	-50	-62	17,4	20,03	16-QAM 1/2	16-QAM 3/4	20	4,3
4	1,15	4,5	-56	-67	6,2	15	BPSK 1/2	QPSK 3/4	22	6
5			-84							8,8
6	1,47	1,29	-61	-73	9,4	8,72	BPSK 1/2	BPSK 1/2	37	6,5

The planned sites introduced in the Chapter 5 were not tested, but based on the results it does not seem possible to establish connection to those points. Besides the coverage and the capacity there are few interesting points that can be seen from the Table 7.5. First of all the effective SNR of the downlink is noticeably low in the points two, four and six although based on the Receiver Signal Strength Indicator (RSSI) the values of the effective SNR should be much higher. This was assumed to be caused by the blocking or front end overloading of the CPE. Near the mast there was two powerful DTT signals one and two channels away as mentioned before. The spectrum from the CPE side measured in point six is presented in the Figure 7.14. The Figure 7.14 shows the WiMAX base station beacon signal on the frequency band 703.5 – 708.5 MHz which is between the two blocks from the left in the figure. Then there is 9.5 MHz guard band to the first TV channel which starts from the fifth block from the left in the figure. From the figure it can be approximated that the difference between the WiMAX beacon signal power and the DTT transmission is 35 – 40 dB.

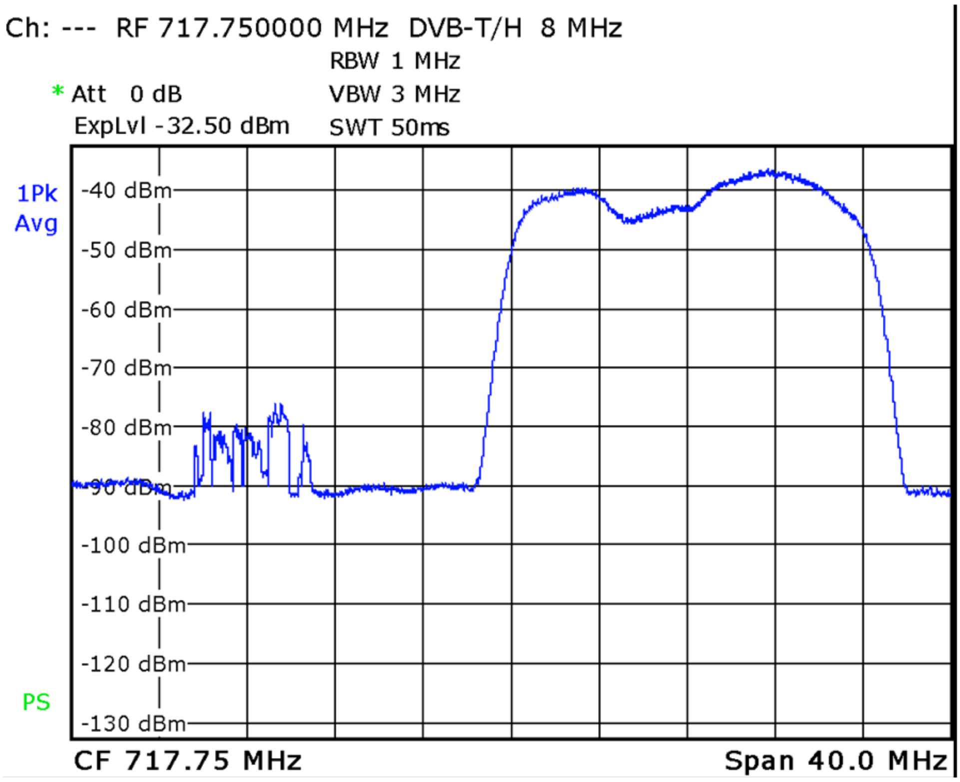

Figure 7.14 *The spectrum measured from the CPE antenna in the measurement point six.*

The relation between the WiMAX signal and the DTT signal was found to depend on the height of the receiver antenna and also on the location. As can be seen from the Table 7.5 in third measurement point the downlink signal was much better than in the points nearer and farther away from the mast. By lowering the receiver antenna height it was also possible to enhance the quality of the downlink signal, but this resulted also on the degradation of the uplink signal. The solution would be to use a channel filter on the channel 50. This increases the noise level of the receiver chain, but clearly it seems that the filter could raise the downlink capacity.

There is also one more interesting result from the measurements. As we can see from the Table 7.5 the RSSI of the uplink seems to be somewhere around 10 dB less than the RSSI of the downlink. In the case of fixed connection the path loss from the base station to the CPE should be exactly the same than from the CPE to the base station. Normally the CPE uses lower transmission power, which is then compensated in the base station end because due to the better radio frequency equipment the receiver sensitivity of the base station is better. In this case however the CPE's reported maximum transmission power is 26 dBm and the base station's 27 dBm. Even thought the transmission power reported by the CPE would not be totally accurate it still would not explain a 10 dB difference. Part of the explanation could be in the way the devices calculate the channel power but that is also not likely to cause this big difference. A close studying of the devices is in place before the next measurements to see if the connection could be enhanced by changing the configuration of the devices.

8 SUMMARY AND CONCLUSIONS

In this thesis the topic of white space network planning and interference estimation has been discussed with special emphasis on the rural broadband case. This thesis has covered different aspects of the white space rural broadband planning with special focus on a pilot case building a fixed wireless broadband network from the Espoo TV and Radio mast to Kirkkonummi. Most important steps in the planning process have been, first of all determining the free frequency band for the white space network so that no interference is caused to the DTT network. Secondly the downlink coverage and capacity planning to see if the intended network is possible in the downlink direction. And lastly the uplink co-channel interference estimation with the Matlab and the uplink coverage and capacity calculations based on the interference level in the intended channel. Two different kinds of field measurements were also carried out in this thesis. The first set of measurements was spectrum measurements from three different locations. These measurement results were used to evaluate the functioning of the Matlab interference estimation method. The second measurements were the connection measurements from the established network in the Espoo and Kirkkonummi area. These measurements were carried out with the Digita's measurement van and using a 10 m receiver antenna height.

The accuracy of the estimation function seemed satisfying for coarse estimation purposes and most of the unquestionably false estimations were in such cases that it would not matter in the planning process. The network coverage field tests showed that it was not possible to establish connection to the intended sites. The range of the network was somewhere around 6 – 7 km whereas at least 10 km range would have been needed. However, the field test results were nicely in line with the uplink prediction. Despite the fact that the implementation of the planned network was not possible, the pilot cannot be said to have failed. Valuable information was obtained in the process about the different aspects of the white space operation. For example using the same mast with the primary DTT transmitter for the white space operation has not been tried before. Interesting results were that operation of the white space base station was not affected by the high power transmitter in the same mast. On the other hand in the downlink direction the CPE receiver's front end was probably overloaded by the high power DTT transmission in the second adjacent channel.

Although the acquired general information and developed methods can be exploited also in the future with different equipment, it is good to keep in mind the limitations of the used equipment. The WiMAX equipment are not designed for the white space operation. Due to the frequency band limitations of the devices , the used channel does not comply with the ECC proposal, with the antenna height and EIRP used in the pilot. Also in the actual WSD's there is probably made an effort to make the devices as robust for the DTT interference as possible.

Future work could include first of all developing the interference estimation function with reliable low level DTT transmission signal powers. At this point the reference signal powers for the estimator did not include the lowest signals levels because the spectrum analyzer dynamic was not sufficient to measure them reliably. Also adding the foreign DTT transmitters to the transmitter file is vital to avoid situations like in the Espoo case. Besides this it would be important to study the optimization of the base station antenna height to find the optimal balance for the downlink and the uplink coverage. There is no point in building networks that have bigger coverage in the downlink than in the uplink direction. Lowering the antenna lowers the co-channel interference power, which enhances the uplink capacity, balancing also the downlink and the uplink capacity.

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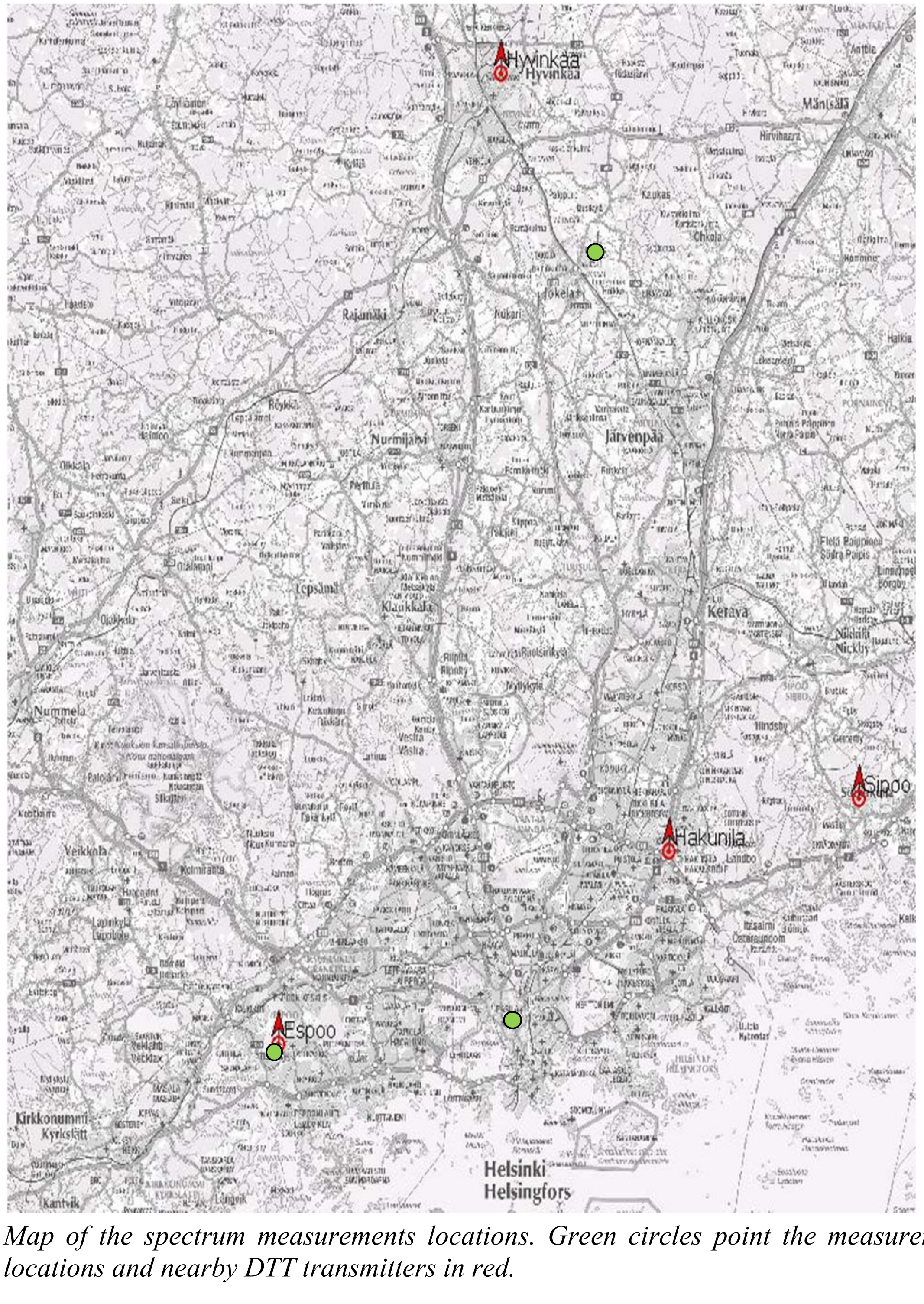
APPENDIX: LOCATIONS OF THE SPECTRUM MEASUREMENTS



Map of the spectrum measurements locations. Green circles point the measurements locations and nearby DTT transmitters in red.